ELECTROMAGNETIC PULSE SOUNDING FOR GEOLOGICAL SURVEYING WITH APPLICATION IN ROCK MECHANICS AND RAPID EXCAVATION PROGRAM

The Ohio State University

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ABSTRACT

A concise discussion of research progress on Contract H0210042 for the period 22 February 1971 to 22 August 1971 is presented. Analytical results on the scattering by various planar and spherical con-cuctivity contrasts and on design data for an electromagnetic pulse sounding probe are described and illustrated. A first generation version of the probe is given and initial measured data demonstrating certain features of the probe are presented.

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I. TECHNICAL REPORT SUMMARY

A unique electromagnetic pulse sounding technique for the detection and diagnosis of geological and man-made anomalies within the earth is being investigated. The immediate application of this technique is as a hazard detection tool in advance of hard rock rapid tunneling operations, but other potential uses can be envisioned. The goals of the program during this contract period are to design and build an electromagnetic probe which effectively couples electromagnetic energy into the ground, is insensitive to surface targets and with this probe measure the scattered fields from cylinders in a rock medium.

The primary goal of this effort is the detection of discontinuities that represent hazards for hard rock tunneling operations. The effort has been separated into two approaches, one theoretical, the other experimental. While it is recognized that the experimental work is the most important part of the project, the theoretical program has been initiated first while equipment has been obtained and interfaced so that the experimental aspects of this research effort can be successfully pursued. The system that has been used consists of a source which produces a periodic train of video pulses. These are coupled to the ground by a broadband probe. The probe does not respond to the ground interface and the pulsed energy has been successfully coupled into the ground over the broad frequency band contained in the transmitted pulse. Nor does it appear to respond to large structures above the ground. A station wagon has not been detected when driven between the antenna elements. Techniques are currently being pursued to achieve the same goal for a rock subsurface medium. The probe consists of a pair of orthogonally oriented balun fed dipoles stretched over the surface of the earth. A wave is launched on one dipole at the feed point that penetrates into the ground. As it propagates along the dipole, its fringe fields penetrate deeper into the earth. The shape of the dipole has been modified to reduce reflections from the antenna structure itself. It is then terminated by a ground wire at the antenna terminals. Reflections on the wire are minimized by this termination which shows that almost all of the energy is indeed being coupled into the ground. Both the transmitter probe and the orthogonal probe can be used to receive reflected signals. These are observed on the sampling scope which acts as a receiver. In our present system, the computer monitors the sampled voltage and stores this information for further processing and can plot any received waveform. The orthogonal probe "sees" only non-homogeneous targets and hence is ideal for detection of any cylindrical obstruction.

Our measurements revealed that a component of the probe system (balun) which matches the output characteristics of the pulse generator to the input characteristics of the probe was not capable of handling the higher power ranges of the generator for any significant pulse width. This made the actual detection of subsurface targets with this present probe difficult. This is not a basic problem because other components with higher power handling capability are available and have been ordered. A different feed arrangement which eliminates the need for the matching component, albeit with a somewhat higher mismatch, has also been devised. In the meantime, a smaller version of the probe and a much narrower pulse with a higher frequency operating band have been used to demonstrate the feasibility of the pulse sounding approach with measurements of a clay drain tile at a depth of 3 feet. This probe has not at this time been properly matched. However by means of a differencing process in the computer, it has been used to obtain a very distinct scattered pulse from the three foot deep drain. This differencing is a very valuable tool which can be retained in the final system by a simple memory and a simple circuit as a final tuning mechanism. The technique used here was to measure the apparent reflections obtained when the probe is placed over a section of ground in which there are no targets. These reflections from the probe are then subtracted from those when the probe is placed over the drain tile. The reflected pulse obtained in this manner is 10 dB above the residual noise. This new probe eliminates the need of grounding the ends of the dipole and would be adequate for penetration of the hard rock medium. Preparations for measurements at a nearby site which offers anomalies characteristic of hard rock tunneling hazards have been made. These preparations primarily involved equipment and circuitry for non-real time use of the computer. The versatility of the computer is essential in establishing the proper parameters to be monitored and to fix the proper data processing steps, i.e., design of the system can be achieved and verified using computer software without the expense of hardware construction. Once the proper data processing steps are established, these should be replaced by devices designed for those specific tasks in the final system for hazard detection.

Preparations are also being made at the nearby quarry for measurements above a rocky media with no lossy soil layer. This has several advantages and disadvantages. The advantage is that losses and dispersion effects will be reduced and consequently a more distinct scattered pulse will be received from buried objects. The disadvantage is that the system can not be as easily matched and above ground reflection could be more apparent.

The feasibility of electromagnetic pulse sounding as a tool for eliciting the size and shape of geological anomalies within the earth is also to be established. A pulse sounding approach for the interrogation of subsurface targets is predicated on certain advances in identification and discrimination of radar targets and on advances

in antenna design for coupling energy into a lossy medium; both of which were pioneered at this laboratory. The approach also utilizes available computer technology for averaging, differencing and other processing of periodic signals. In a field version system, the computer functions would be replaced by circuitry, but in the research phase the computer again offers an irreplacable versatility in processing techniques.

Simply stated, it has been demonstrated that the physical properties of an object (size, general shape and composition) are adequately defined by the interactions of the object with electromagnetic waves over a frequency range where the object size ranges from small to that comparable to the interrogating wavelength. In terms of geological anomalies of reasonable size, this dictates low frequencies and it is precisely these frequencies which can penetrate the earth to significant depths. Thus the approach is ideally suited for the interrogation of subsurface targets.

At this stage of the contract, analytical tools for studying the scattering of electromagnetic waves by planar and spherical approximations of geological anomalies and for the analysis of electromagnetic probe structures have been developed and are being applied. The need for these calculations is to establish better design parameters for the system and to provide additional data for target identification purposes. The latter study, essentially an analysis of arbitrary wire structures in a dissipative medium, is felt to represent a significant advance in the state-of-the-art. A pulse generator (H.P. 214A) with pulse characteristics suitable for interrogation of anomalies of the order of 10 to 100 feet at depths possibly over 100 feet has been purchased.

In summary, the analytical tools for the design and analysis of an electromagnetic pulse sounding probe have been developed. These same tools will serve to define the basic limitations of the pulse sounding technique. A first version of the probe has been constructed, a power handling problem revealed and solved, and the feasibility of the pulse sounding approach demonstrated via measurements of a shallow subsurface target. The program is proceeding in agreement with the original research plan and no deviation from this plan except possibly a slight delay in the initiation of remote site measurements is anticipated.

II. PURPOSE

A unique electromagnetic pulse sounding technique for the detection and diagnosis of geological and man-made anomalies within the earth is being investigated. The immediate application of this technique is as a hazard detection tool in rapid excavation operations in a hard rock medium. During this contract period the objectives of the program

are to; 1) design and demonstrate a probe structure capable of effectively coupling electromagnetic pulse energy into the ground and at the same time be insensitive to surface scatterers, 2) interrogate with this probe certain simple subsurface targets such as voids and discontinuities representative of rapid excavation hazards, and 3) establish preliminary bounds on the workable depths of electromagnetic pulse sounding via theoretical and experimental methods.

III. INTRODUCTION

The ultimate goal of the research on this program is to incorporate state-of-the-art advances developed at this laboratory, both in antenna systems and processing techniques, into a geological tool capable of delineating the size and shape of geological anomalies from the spectral content of an echo pulse.

If the gross features, i.e., overall size and shape of an anomaly are to be deduced via electromagnetic interrogation then frequencies over an 8 or 10:1 bandwidth with a fundamental such that the linear extent of the anomaly is approximately 1/10 of a wavelength in the medium are dictated.[1] With a pulse sounding approach,* this fixes the characteristics (rise time, repetition rate, etc.) of a pulse generator suitable for a given range of anomaly sizes. It does not necessarily follow that all of the higher spectral content are needed to obtain a viable signature,[2] but the lowest frequencies are essential. Of course, the more high frequency content available the sharper the reflected pulses and consequently an improved range gating. This is an advantage of the hardrock medium over the soil media currently being used in our experimental studies. Thus the approach is ideally suited for subsurface interrogation where low frequencies are needed to obtain significant penetration. Clearly, the attenuation and dispersion of the ground as well as the size and scattering characteristics of a given anomaly bound the maximum working depth of a pulse sounding system. Analytical studies to secure estimates of these limiting effects via plane wave scattering computations for planar and spherical conductivity contrasts are described in Section IV.A of this report.

In Section IV.B, a comprehensive analysis of wire antennas in a homogeneous, dissipative medium is described. Considerable effort has been expended on this study since realistic estimates of penetration depths, dispersion effects and surface target sensitivity for practical probe geometries are a vital requirement of the program. A major feature of the computational programs developed is that the speed and accuracy are sufficient to permit pulse type excitation studies via Fourier synthesis.

*An alternative system for radar applications uses discrete harmonically related cw measurements over the 10:1 bandwidth.[3]

Certain exact, closed form results which can be obtained for the transient fields of an infinite line source in the presence of a half-space are given in Section IV.C. These two-dimensional results are less directly applicable to the immediate problems and have not therefore been extended at this time.

The first generation version of the pulse sounding probe and the results of measurements on this probe are described in Section V. These initial tests were made in the immediate vicinity of the laboratory but the necessary circuitry and equipment for remote site operation are now nearly completed.

A summary of the present status of this research effort and our plans for the remaining contract period are given in Sections VI and VII respectively.

IV. ANALYTICAL STUDIES

A. Scattering Computations

1. Planar contrasts

The plane wave scattering characteristics of a planar contrast between two dissipative media are most simply studied in terms of the impulse response waveform at the interface, i.e., the inverse Laplace transform of the frequency-dependent Fresnel reflection coefficient. For normal incidence and assuming the constitutive parameters of both media are frequency independent, the form of the impulse response waveform is shown in Fig. 1. The response to any other incident waveform is given by convolution as is discussed later. The plane wave is incident from medium 1 into medium 2. The response consists of an impulse singularity of weight

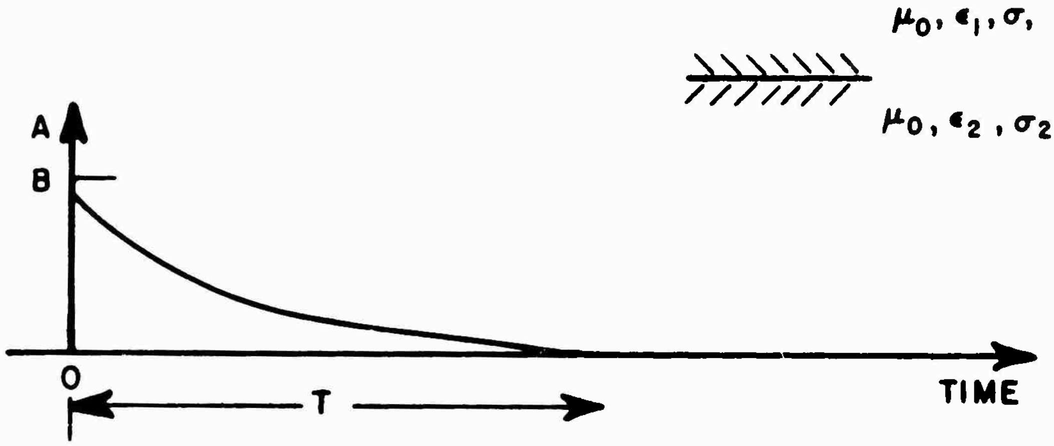
$$A = \frac{\sqrt{\varepsilon_{r1}} - \sqrt{\varepsilon_{r2}}}{\sqrt{\varepsilon_{r1}} + \sqrt{\varepsilon_{r2}}} \quad , \tag{1}$$

a jump discontinuity of magnitude

$$B = \frac{2\sqrt{\varepsilon_{r1}\varepsilon_{r2}}}{\varepsilon_0\left(\sqrt{\varepsilon_{r1}} + \sqrt{\varepsilon_{r2}}\right)^2} \left[\frac{\sigma_2}{\varepsilon_{r2}} - \frac{\sigma_1}{\varepsilon_{r1}}\right] \quad , \tag{2}$$

and then a smooth decay to zero in a time less than the relaxation time (ε_2/σ_2) of medium 2. Note that both the singularity and discontinuity can be of either sign depending upon the relative permittivity and conductivity contrasts. In Fig. 2, the weight of the singularity, A, is shown for permittivity contrasts, $\varepsilon_{r1}/\varepsilon_{r2}$, from 0.1 to 10.0. Fig: 3 shows the quantity $\varepsilon_0\ \varepsilon_{r1}\ B/\sigma_1$ for conductivity contrasts σ_2/σ_1 from 0.1 to 10.0 with the permittivity contrast, $\varepsilon_{r2}/\varepsilon_{r1}$, as a parameter.

IMPULSE RESPONSE WAVEFORM FOR PLANE WAVE REFLECTION AT THE INTERFACE OF TWO LOSSY MEDIA. NORMAL INCIDENCE.



A - WEIGHT OF IMPULSE SINGULARITY, $A = \dfrac{\sqrt{\varepsilon_{r1}} - \sqrt{\varepsilon_{r2}}}{\sqrt{\varepsilon_{r1}} + \sqrt{\varepsilon_{r2}}}$

B - INITIAL VALUE OF WAVEFORM, $B = \dfrac{2\sqrt{\varepsilon_{r1}\varepsilon_{r2}}}{\varepsilon_0\left(\sqrt{\varepsilon_{r1}} + \sqrt{\varepsilon_{r2}}\right)^2}\left[\dfrac{\sigma_2}{\varepsilon_{r2}} - \dfrac{\sigma_1}{\varepsilon_{r2}}\right]$

T IS LESS THAN THE RELAXATION TIME$\left(\dfrac{\varepsilon_2}{\sigma_2}\right)$ OF THE MEDIUM

Fig. 1. Sketch of impulse response waveform of planar contrast.

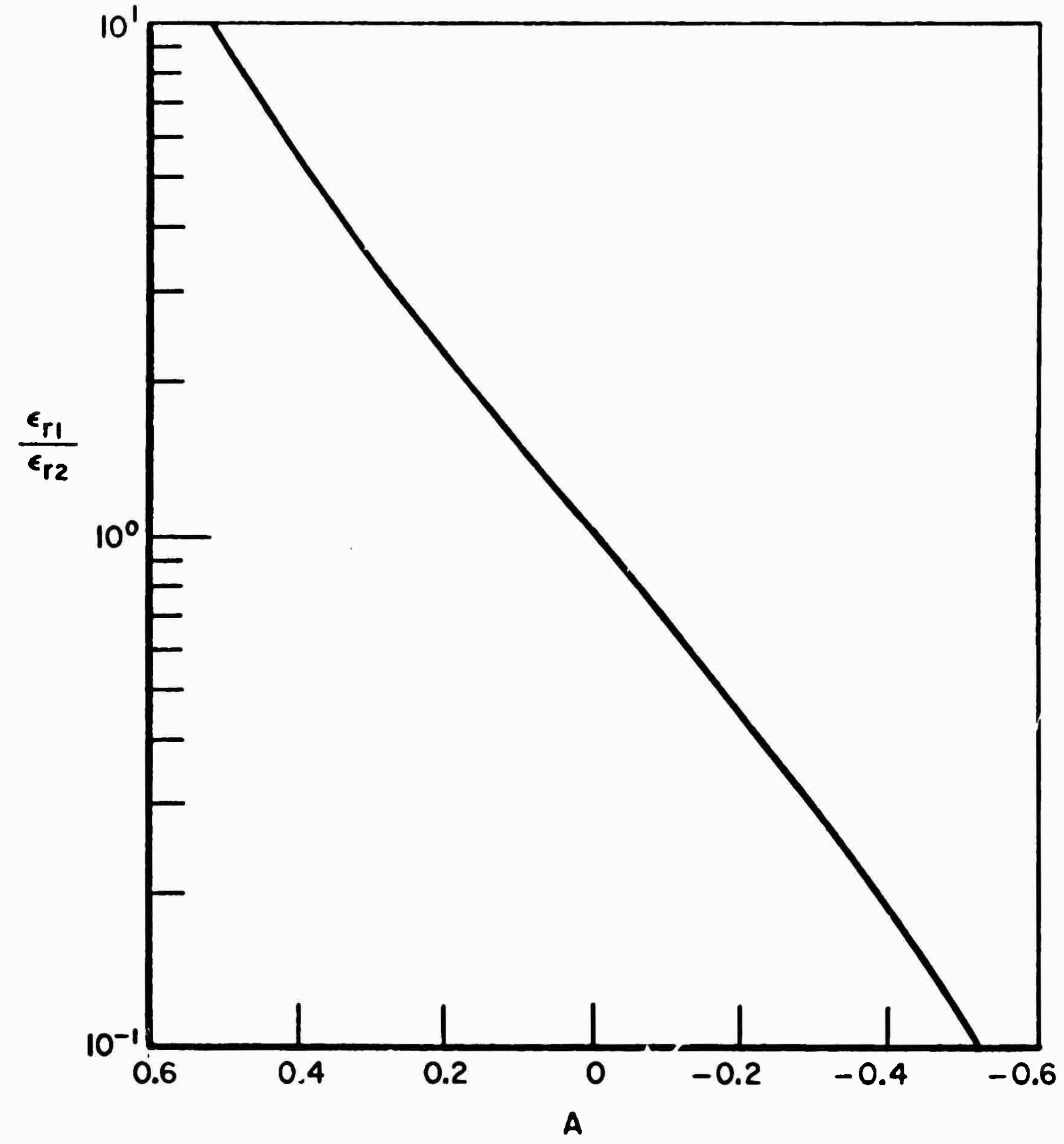


Fig. 2. Weight of impulsive singularity.

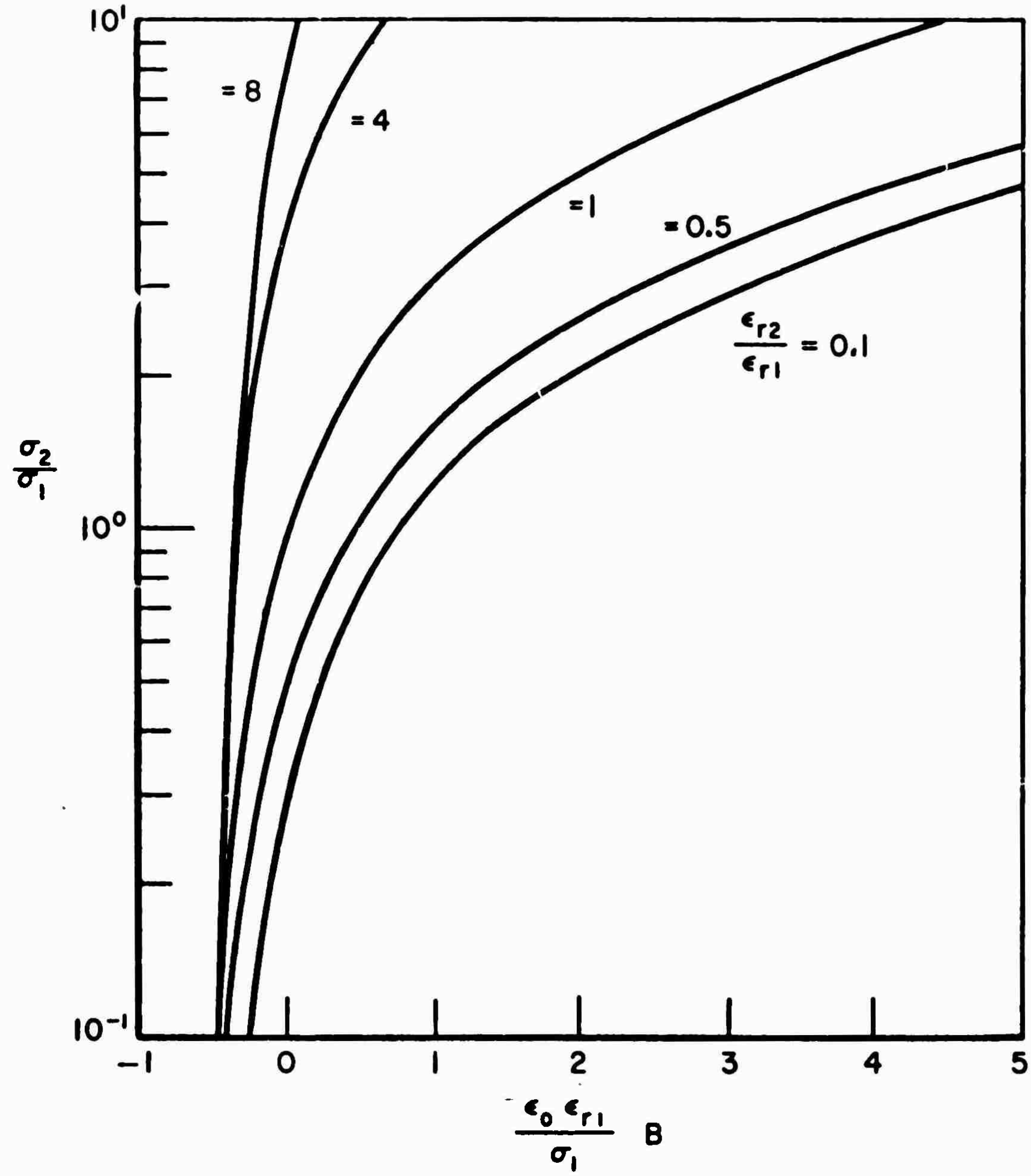


Fig. 3. Magnitude of step discontinuity.

Details of the decay rate of the waveform are best obtained via a Fourier synthesis procedure[4] where the response waveform is constructed from calculations of the frequency-dependent reflection coefficient at harmonically related frequencies. Examples of such waveforms are shown in Figs. 4 and 5. To simplify the synthesis procedure, the impulse singularity has been subtracted from the reflection coefficient before synthesis. The synthesis procedure also permits one to introduce frequency-dependent constitutive parameters in both media since calculations of the reflection coefficient at discrete frequencies are made. In this case the constitutive parameters used to calculate the quantities in Eqs. (1) and (2) should be those the media approach in the high frequency limit.

Given the impulse response waveform for a planar contrast, the response for an interrogating plane wave with an arbitrary time dependence is easily obtained by convolution.[1] Note specifically that the convolution computations do not require analytical expressions for the impulse response waveform, which are obviously not obtained when the Fourier synthesis procedure is used. The most serious drawback to the results given here is the assumption of an impulsive plane wave incident from medium 1. If this medium is very lossy then the assumption is poor when one considers an air-earth interface above medium 1. This could be corrected if the dispersive properties of the medium are known. However, if medium 1 is essentially a dielectric, e.g., hard rock which might be expected at the face of a tunneling operation, then the impulsive assumption is a good one.

The planar contrasts have a distinctive signature which has diagnostic features in the sign and magnitude of both the impulsive singularity and the jump discontinuity and in the effective duration of the waveform. it is clear that a reasonable approximation for the impulse response waveform is

$$(3) \qquad F_I(t') \simeq A\delta(t) + Be^{-\alpha t/T_r}\mu(t),$$

where A and B are defined in Eqs. (1) and (2), T_r is the relaxation time for medium 2. ($T_r = \epsilon_2/\sigma_2$) and α is an adjustable parameter. Sufficient computations to estimate α over a range of contrast parameters will be made.

2. Spherical contrasts

The Mie series resulting from a modal solution of the plane wave scattering by a spherical target has been programed for the IBM 360 computer for 2 cases: a lossy sphere in a dissipative ambient medium and a lossy sphere with a lossy layer in a dissipative ambient medium.

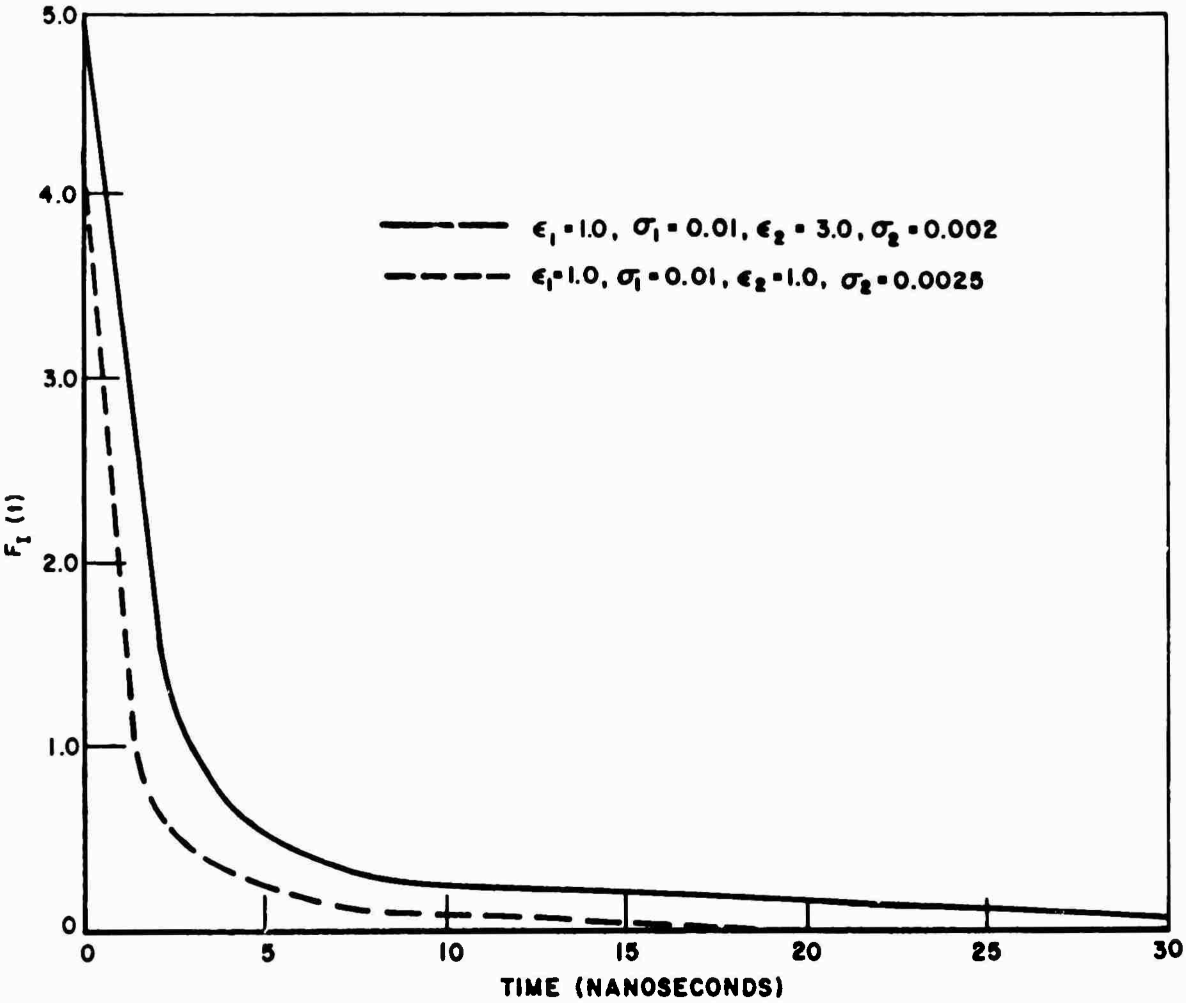
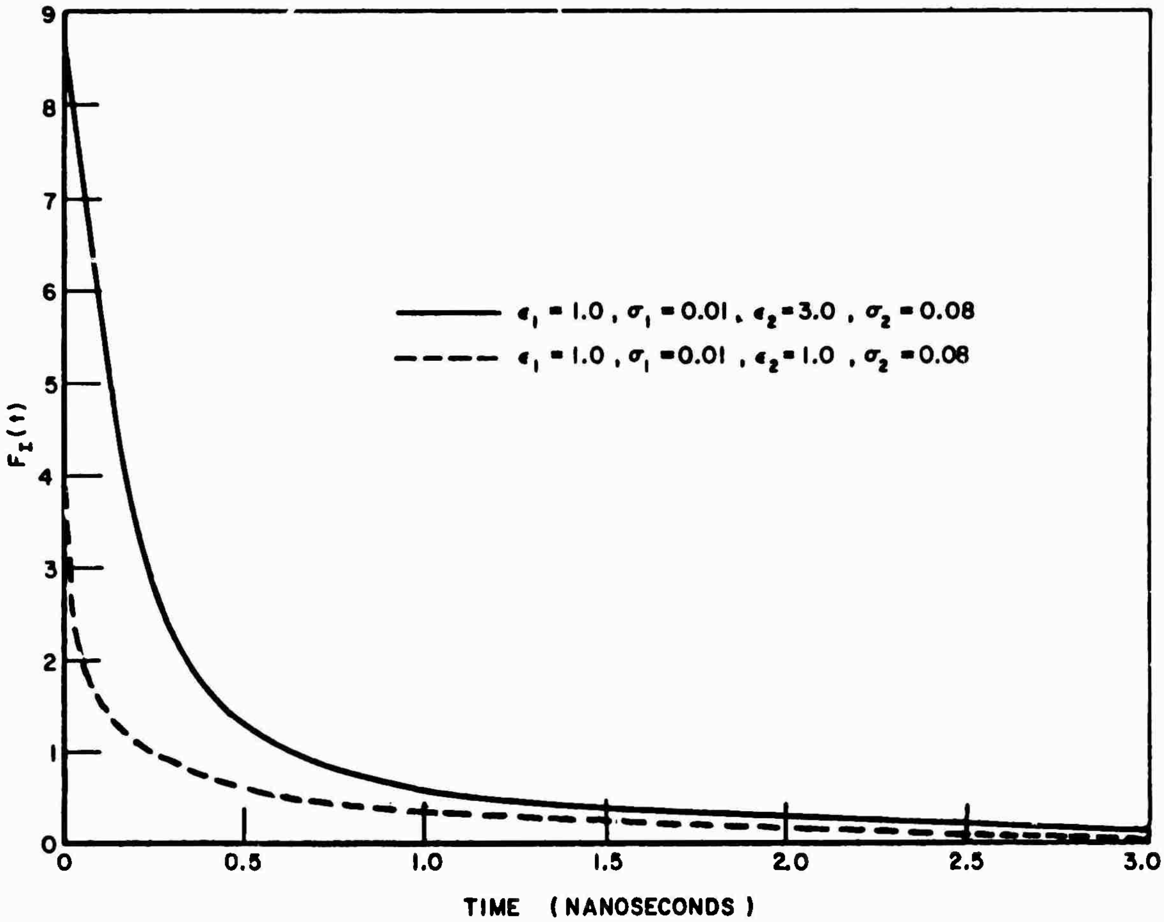
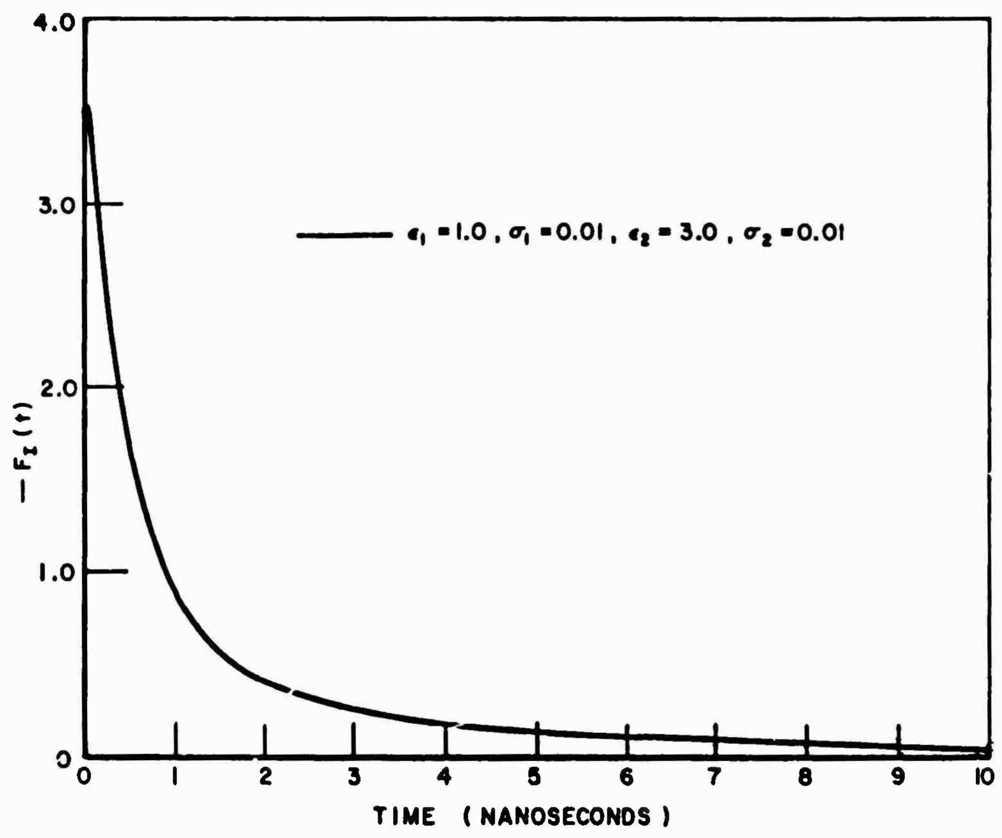


Fig. 4. Impulse response waveforms of planar contrast, impulse singularity removed.



(a)

Fig. 5a,b. Impulse response waveforms of planar contrast, impulse singularity removed.



4.0
3.0
2.0
1.0
0
$-F_I(t)$
$\epsilon_1 = 1.0$, $\sigma_1 = 0.01$, $\epsilon_2 = 3.0$, $\sigma_2 = 0.01$
0
1
2
3
4
5
6
7
8
9
10
TIME (NANOSECONDS)

(b)

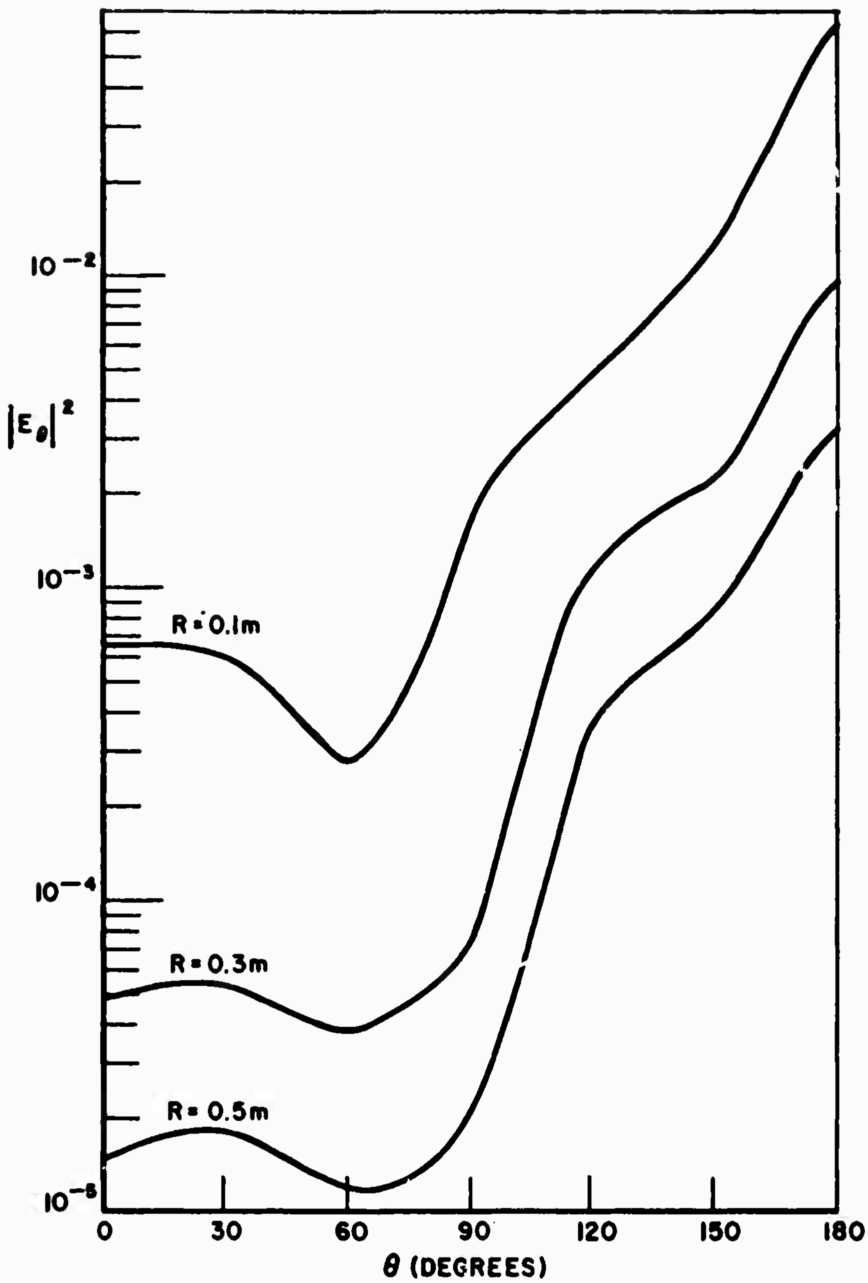
Fig. 5. (Cont.)

As with the planar contrast, the assumption of a plane wave incident on the target places restrictions on the ambient medium. With these programs, formulation of the transient response waveforms via Fourier synthesis is feasible. At present the computations have been confined to single frequencies, primarily to ensure that all bugs have been removed from the programs.

Examples of the computations for spherical targets are shown in Figs. 6, 7, and 8. In Fig. 6 the E-plane (6a) and H-plane (6b) patterns showing the magnitude of the scattered field squared as a function of bistatic angle are shown. Zero degrees is backscatter. The sphere in Fig. 6 is a lossless dielectric, $\varepsilon_r = 2.8$, with a radius of 5 cms. The ambient medium has a wavenumber $k_m = 99.48 + j0.2973$ so that the index of refraction for the sphere is 1.056 - j0.003. The frequency is 3.0 GHz. Patterns are shown in Fig. 6 for observer ranges of 0.1, 0.3 and 0.5 meters. In Fig. 7, similar results for a lossy sphere ($\varepsilon_r = 11.0$, $\sigma = 0.385$, loss tangent = 0.210) with a radius of 5 cms are shown. The ambient medium and the frequency are the same as those in Fig. 6. Finally, in Fig. 8, results are shown for the same conditions as Fig. 7 but a lossy layer 1 cm thick ($\varepsilon_r = 11.0$, $\sigma = 0.0025$, loss tangent = 0.00136) has been added to the sphere. It should be noted that for economy reasons the angular increment for these computations (Figs. 6, 7 and 8) was quite large (30°), thus some fine detail of the curves may not be shown. The data shown were primarily run to check out the computer programs. These programs are efficient, but the cost of such calculations is not trivial. Thus, some effort to estimate parameters for the ambient medium and spherical targets which are realistic models of tunneling hazards will be expended before extensive calculations are made.

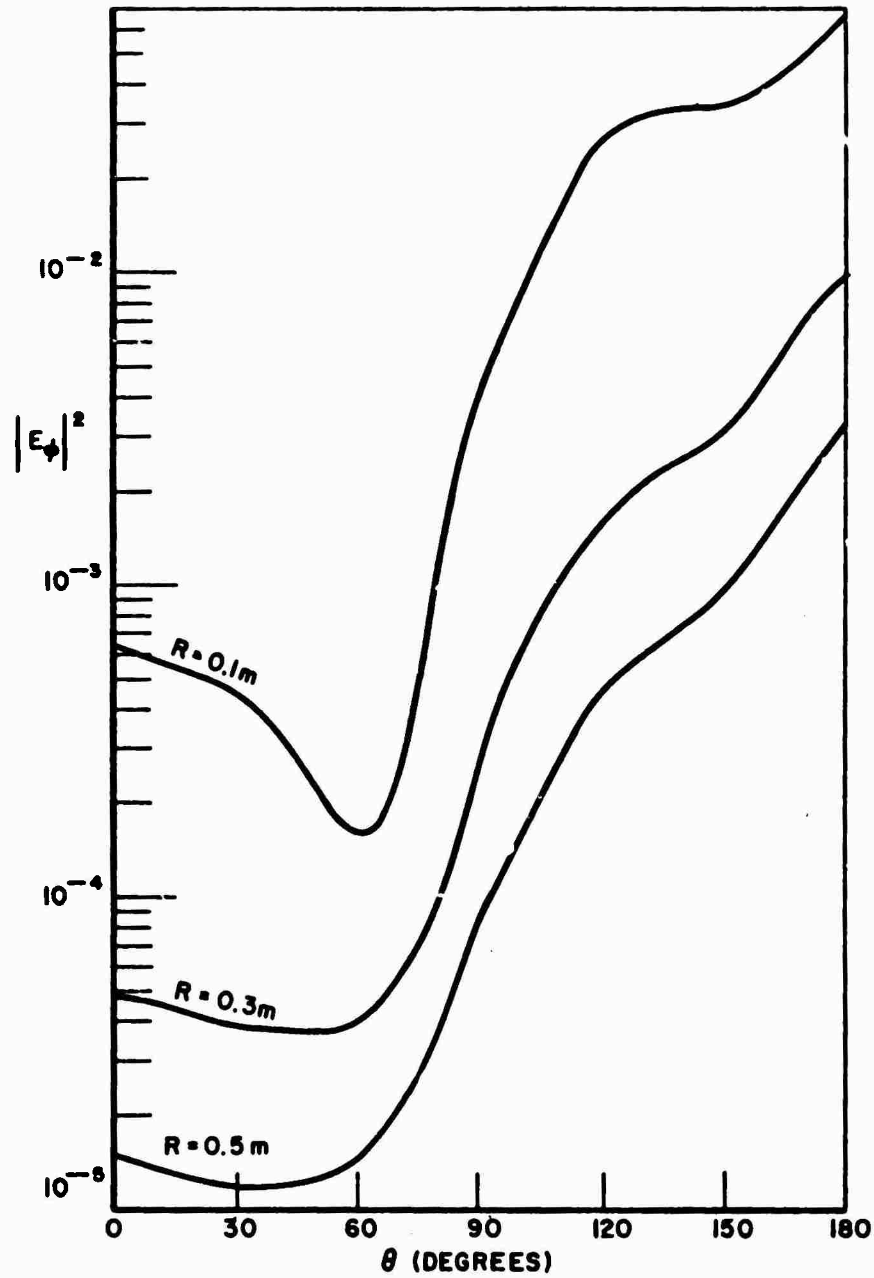
3. Overburden effect estimates

The effects of the air-earth interface and propagation in the ground on the plane wave interrogation of a buried target has been estimated in the following manner. A plane incident wave at an off-normal angle from the earth surface is assumed. The transmitted field at a given depth is calculated under the assumption of frequency independent constitutive parameters for the earth. This field is then modified by the known scattering characteristics (amplitude and phase) of the target in free space at an equivalent (same electrical size) frequency. The propagation path to the surface is retraced and the field then transmitted through the earth-air interface. It is desired to compare the ramp response waveform of the target in free space and in the earth. This is done via a Fourier synthesis procedure with calculations as described above at discrete harmonically related frequencies. For the ramp response waveform (twice integrated impulse response) only a very few frequencies are needed.[2] It is interesting that two different ramp response waveforms for the target



(a)

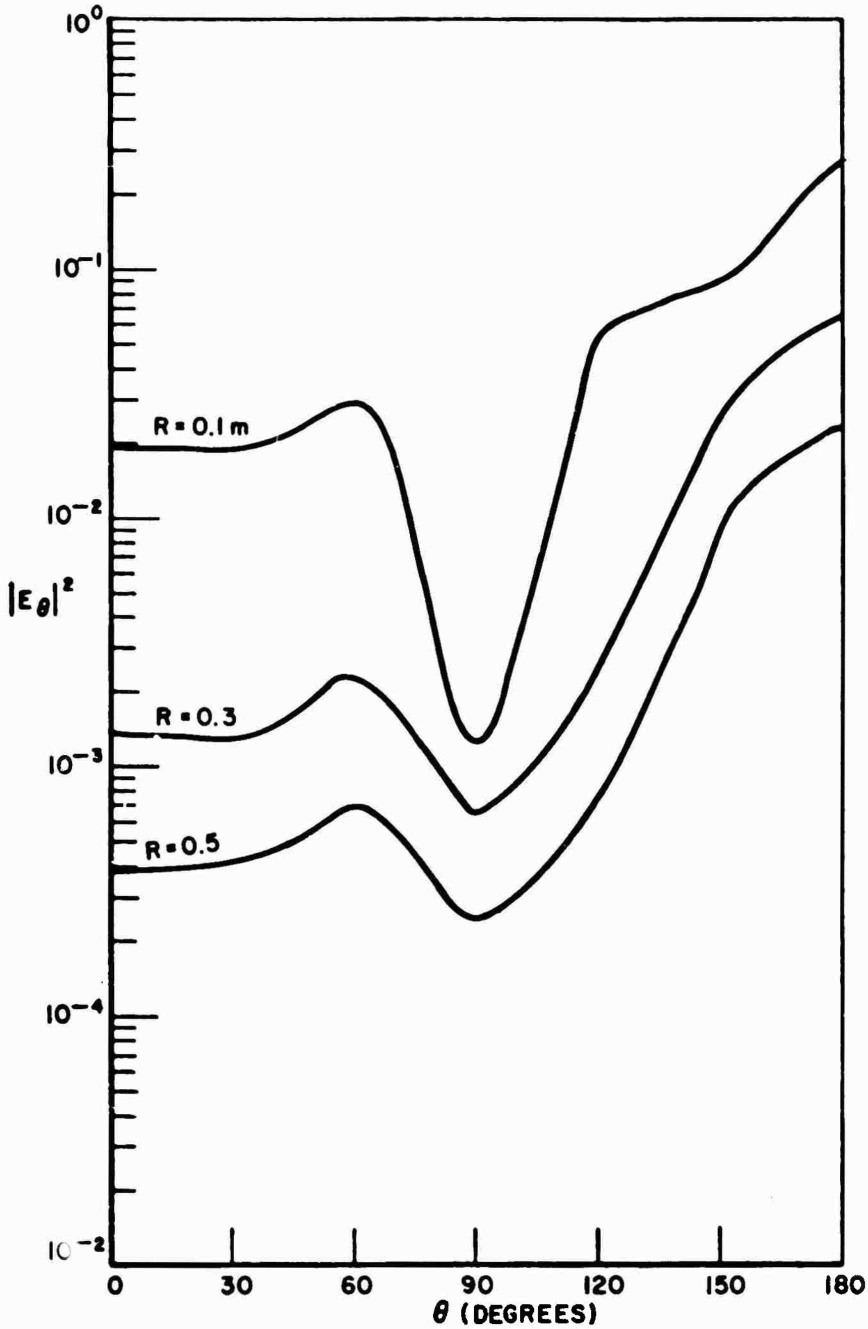
Fig. 6. Magnitude squared of scattered field vs bistatic angle lossless dielectric sphere in a lossy medium. (a) E-plane, (b) H-plane.



10^{-2}
10^{-3}
10^{-4}
10^{-5}
$|E_\phi|^2$
R = 0.1m
R = 0.3m
R = 0.5 m
0
30
60
90
120
150
180
θ (DEGREES)

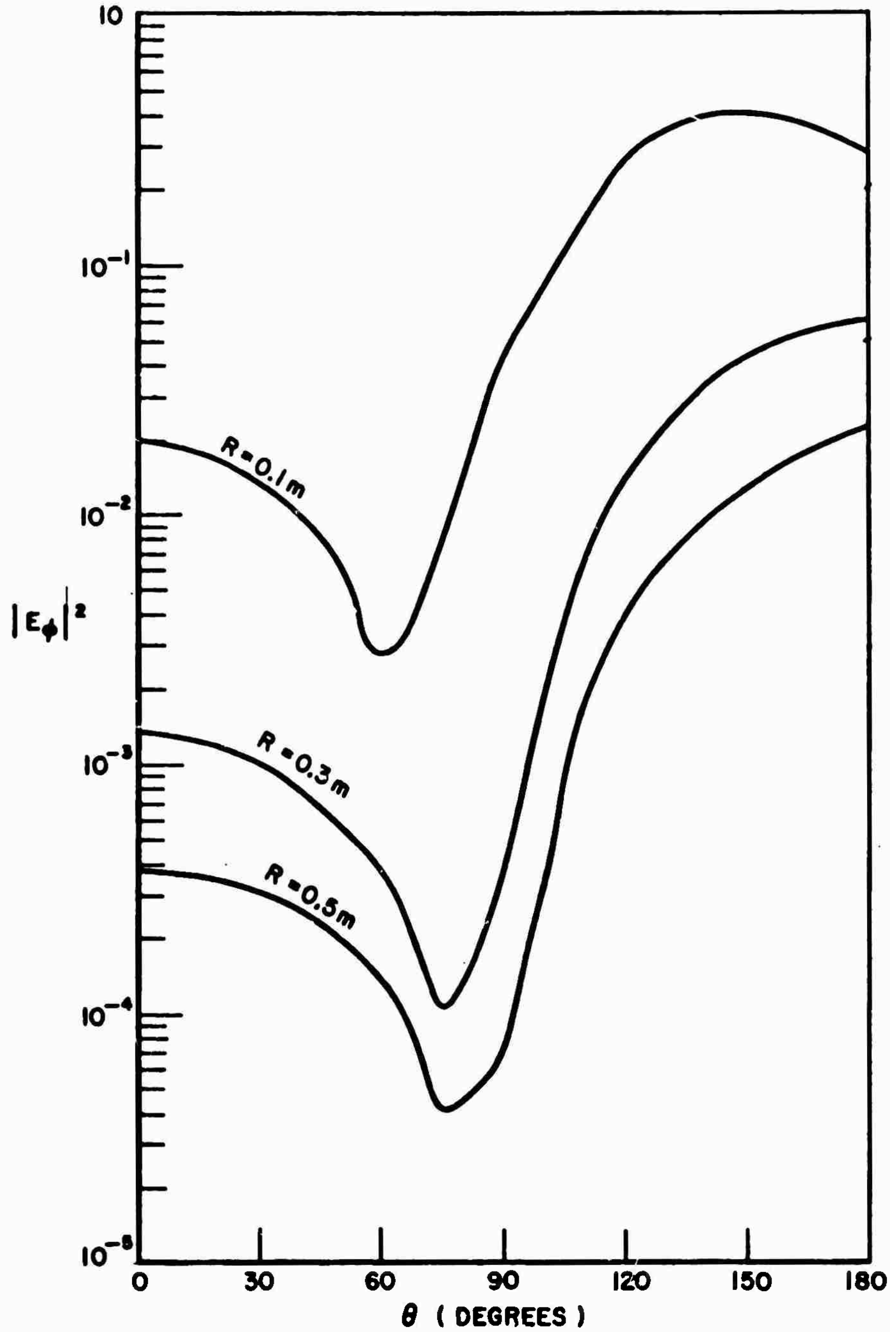
(b)

Fig. 6. (Cont.)



(a)

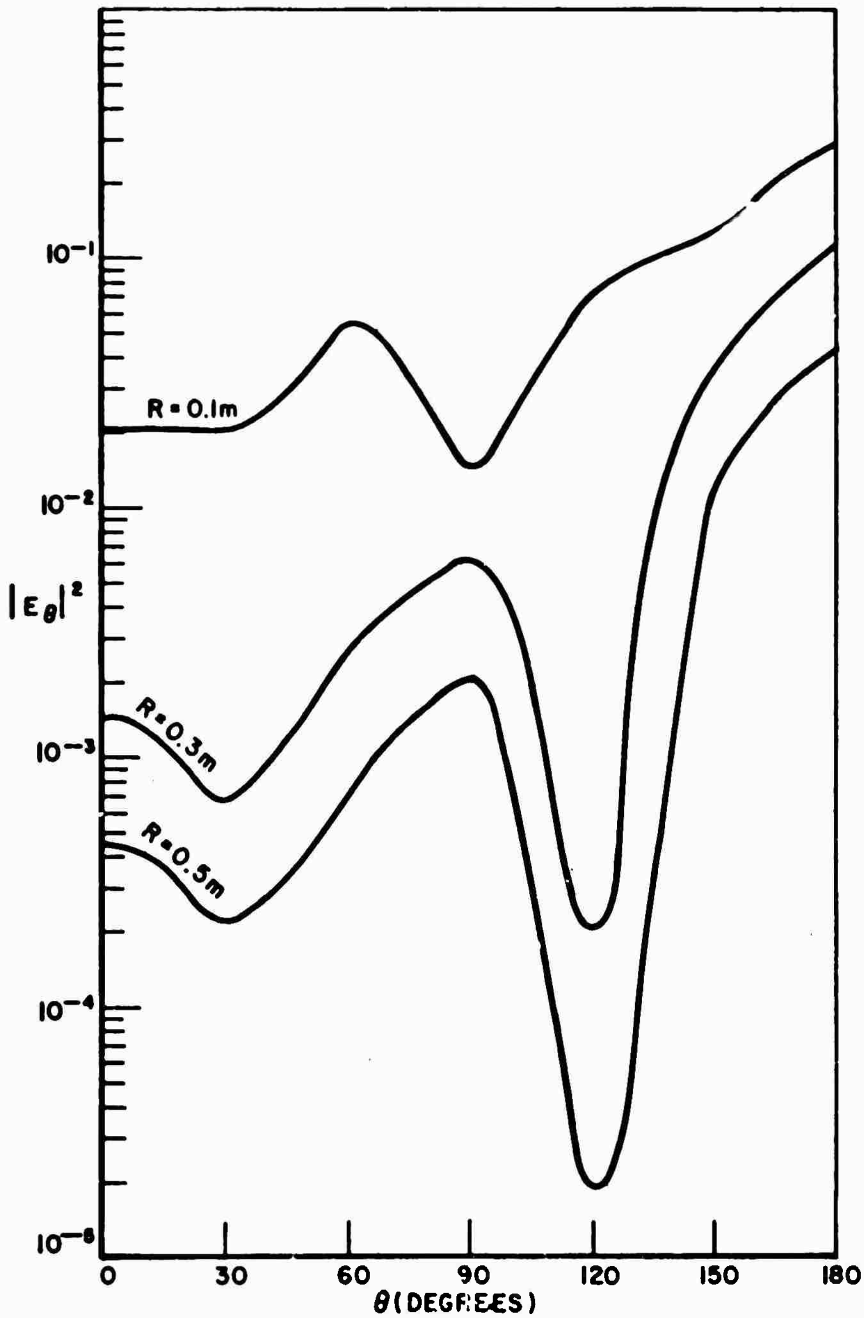
Fig. 7. Magnitude squared of scattered field vs bistatic angle for a lossy dielectric sphere in a lossy medium. (a) E-plane, (b) H-plane.



10
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
$|E_\phi|^2$
R=0.1m
R=0.3m
R=0.5m
0
30
60
90
120
150
180
θ (DEGREES)

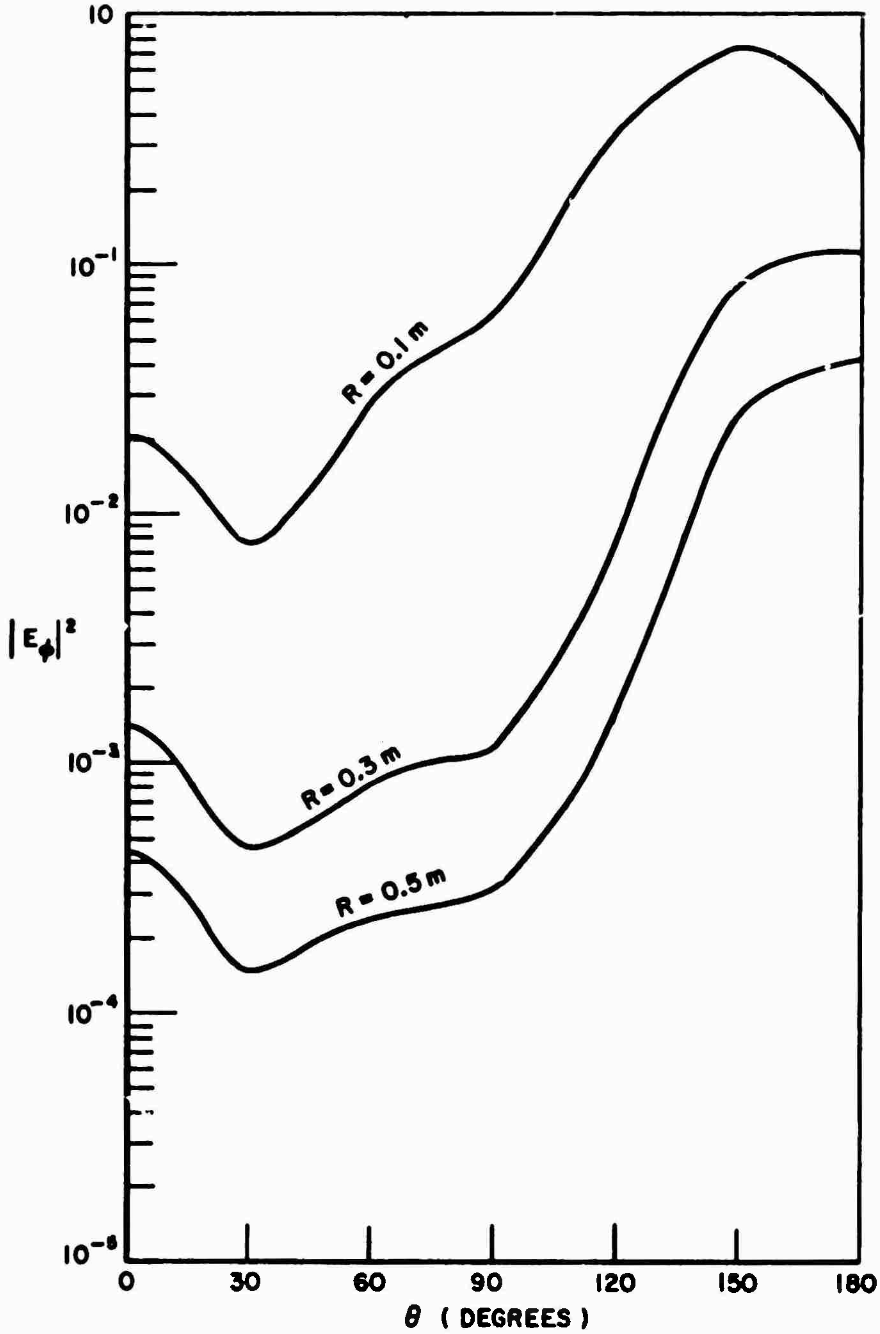
(b)

Fig. 7. (Cont.)



(a)

Fig. 8. Magnitude squared of scattered field vs bistatic angle for a layered lossy sphere in a lossy medium. (a) E-plane, (b) H-plane.


10
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
$|E_\phi|^2$
R = 0.1 m
R = 0.3 m
R = 0.5 m
0
30
60
90
120
150
180
θ (DEGREES)

(b)

Fig. 8. (Cont.)

can be obtained. In each case the fundamental frequency is calculated such that the requirements on electrical size in the medium described in the Introduction are met. This calculation is made under the assumption that the earth is a conductor, i.e.,

$$(4) \qquad \lambda \text{ medium} \simeq \frac{2\pi}{\sqrt{\pi f \mu_o \sigma_m}} .$$

If the required harmonic wavelengths are calculated from Eq. (4) then one response waveform results. This is case of the ramp waveform incident at the target. If one simply takes multiples of the fundamental then a different waveform is obtained. This is the case of a ramp waveform on the transmitting cable. The difference is essentially that of taking the harmonics as $n\omega_0$ or $n^2\omega_0$ (Eq. (4)) where ω_0 is the fundamental angular frequency. In practice, either definition could be used provided the period T of the transmitted waveform is sufficiently large that the reflected signal from the target is completely damped out before the onset of the next pulse. This implies a narrowly spaced spectrum over the frequency band of interest and consequently, one could reconstruct via the computer either of the incident ramp waveforms. In Figs. 9, 10 and 11 the free space and underground ramp response waveforms for a conducting sphere, conducting cylinder and conducting disk are shown. The time scale in these figures is in units of the period of the fundamental synthesis frequency. The ground parameters are taken as $\epsilon_r = 10.0$, $\sigma = 6.11 \times 10^{-4}$ and the targets are at a depth of 30 meters. The interrogating waveform (periodic with ramp discontinuities) is incident at an angle 30° from normal with the electric field parallel to the ground. The targets have a characteristic dimension of 6 meters, i.e., sphere, disk and cylinder have a radius of 3 meters. The cylinder has a 2:1 length to diameter ratio. The axis of the cylinder is parallel to the ground interface and to the incident electric field, the disk is perpendicular to the ground interface with the plane of the disk parallel to the incident electric field. 10 harmonic frequencies were used to produce the waveforms shown. For each target it is seen that the interface and ground propagation has distorted the free space waveform, yet the distortion is not such as to preclude a signature assignment. The known relationships[4] between the physical properties of the target and its free space ramp response waveform have been distorted and clearly, as was anticipated, development of such relationships for subsurface targets will be more difficult than for the free space case. There is, however, no evidence to indicate that the effects of the interface and overburden will negate a time domain signature approach.

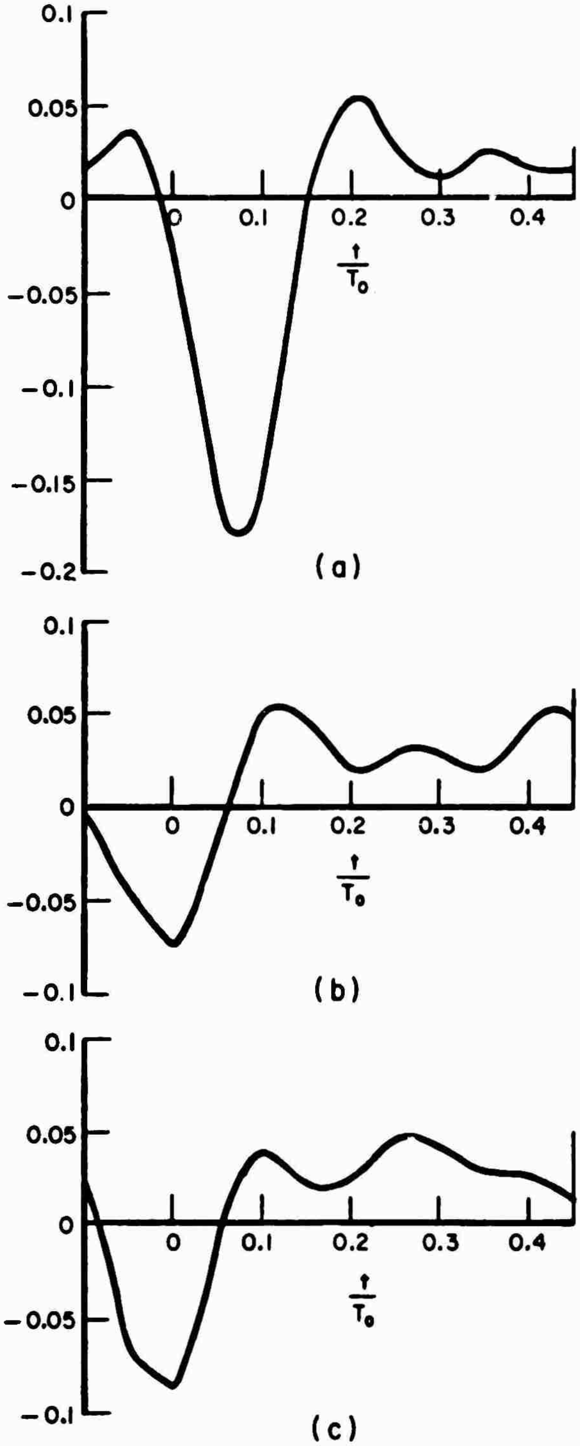


Fig. 9. Ramp response waveforms of a conducting sphere:
(a) free space,
(b) underground - $n\omega_0$ harmonics,
(c) underground - $n^2\omega_0$ harmonics.

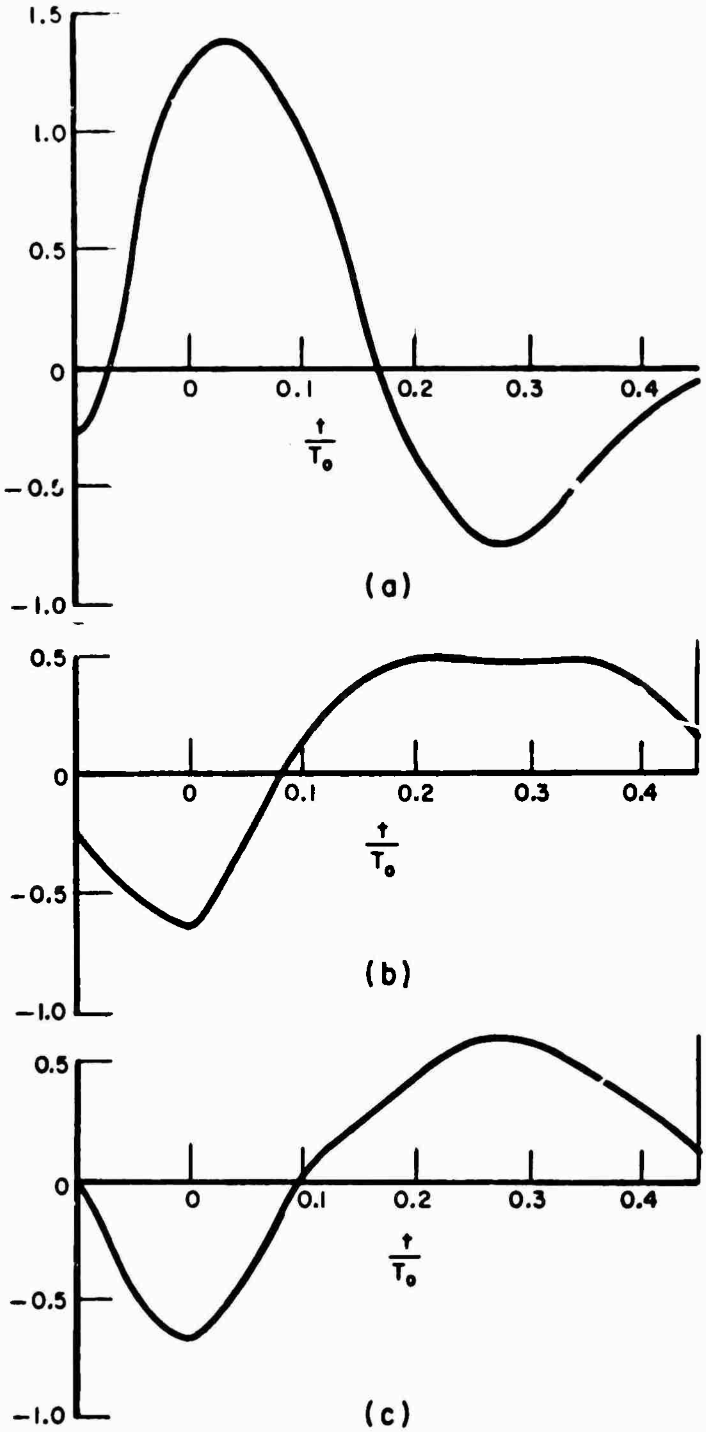


Fig. 10. Ramp response waveforms of a conducting circular cylinder:
(a) free space,
(b) underground - $n\omega_0$ harmonics,
(c) underground - $n^2\omega_0$ harmonics.

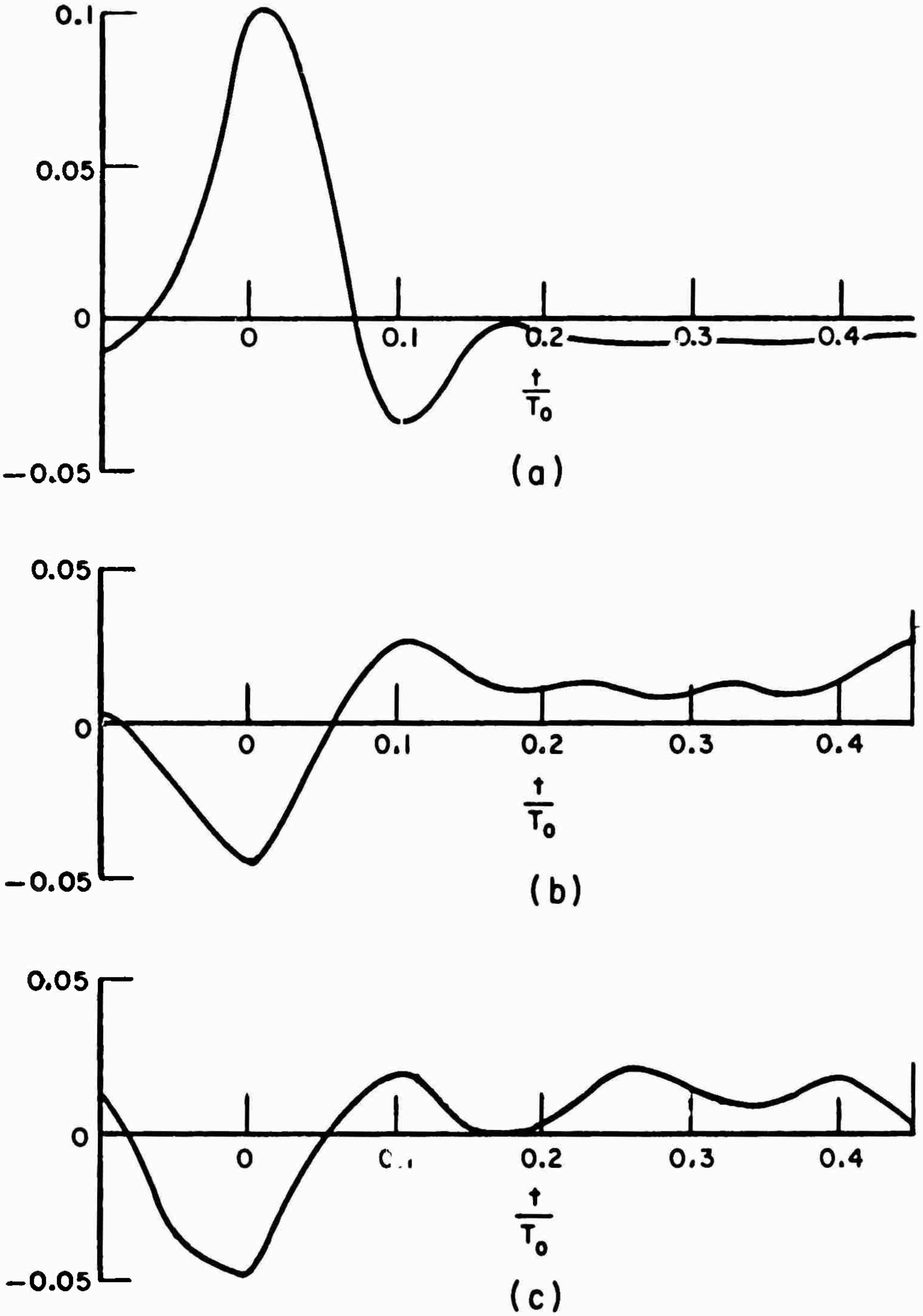


Fig. 11. Ramp response waveforms of a conducting disk:
(a) free space,
(b) underground - $n\omega_0$ harmonics,
(c) underground - $n^2\omega_0$ harmonics.

B. Probe Analysis and Design

We have developed a comprehensive analysis and computer program for wire antennas in a homogeneous dissipative medium. The program handles all types of wire antennas including linear dipoles, V dipoles, rectangular loops, circular loops and arrays. The output provides a complete analysis of the system, including self impedance, mutual impedance, current distribution, near-zone fields, and far-field patterns.

The finite conductivity of the wire antenna is taken into accoun via the surface-impedance formulation. If some portions of the antenna are insulated from the conducting medium by a thin dielectric sleeve, this is taken into account via the equivalent polarization currents.

A piecewise-sinusoidal expansion is employed for the unknown current distribution on the antenna, and Galerkin's method is used to reduce the integral equation to a system of simultaneous linear equations. The analysis takes place in the frequency domain. The speed, accuracy and generality are sufficient, however, to permit a Fourier transform to the time domain.

Figure 12 illustrates typical data obtained with this computer program. This figure shows the near-zone electric field distribution E_x of a U-shaped wire antenna at 100 KHz. The observation point is on the z axis where E_y vanishes and E_z is much smaller than E_x. The solid curve shows the field distribution of the uninsulated antenna, and the dashed curve shows the effect of insulating the horizontal portion of the antenna. The input power was one watt in both cases. The polystyrene insulation has an inner diameter of 3/8 inch and an outer diameter of 3/4 inch.

The data in Fig. 12 indicate that the uninsulated antenna may be advantageous for detection of targets at close range. Of greater importance is the fact that the computer program can be employed to optimize the antenna design for a given target position, frequency range, and soil conditions.

The expansions published by Banos will be programed to account for the effects of the air-earth interface. When this is completed, the computer program will be applied to the analysis and design of probes for the electromagnetic pulse-sounding system.

C. Transient Fields of a Line Source

Thus far we have considered plane wave incidence for the geometries of interest. It is important to obtain incident fields for different sources since it is not desirable to illuminate the target with a plane wave. While the technique just discussed gives the

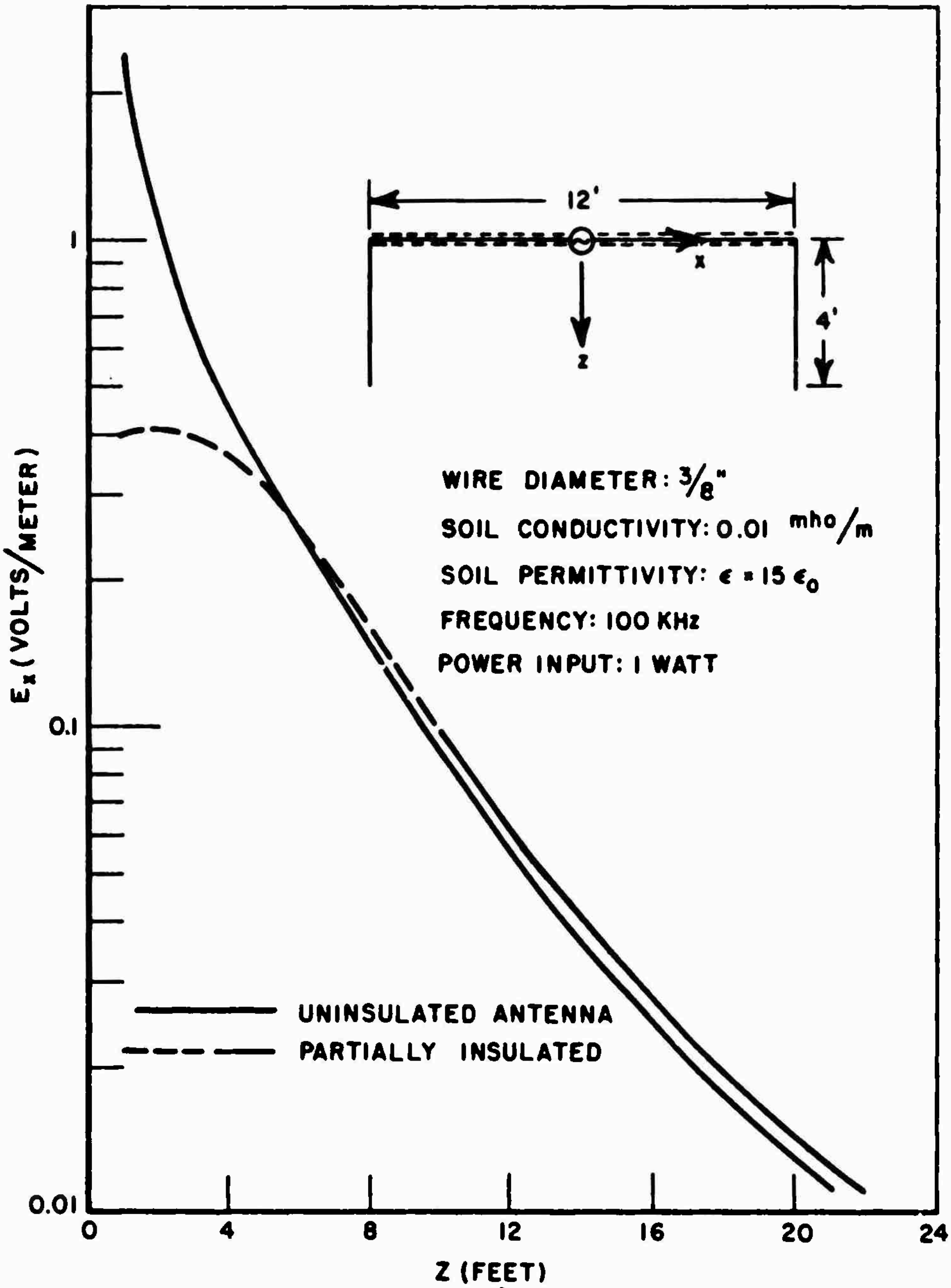


Fig. 12. Calculated electric field distribution of a wire antenna in a homogeneous conducting medium. The observer is on the z axis.

fields for the actual sources of interest, it does this in a quantitative way. It is equally important to evaluate the fields of various sources in functional form so that a more thorough understanding of the physical mechanisms involved can be obtained. The line source above an interface is most important since simple exact closed form expressions can be obtained.

Let a rectangular coordinate frame be oriented with the xy plane on the surface of a half-space with the z axis perpendicular to the half-space and positive into the half-space. A harmonic line source is oriented parallel to the y axis at a height -h above the half-space. The half-space is assumed to be homogeneous and isotropic with constitutive parameters ε_1, μ_0, σ_1. If the observation point is confined to the z axis (x=0) and the half-space is lossless (σ_1=0) then it can be shown that a change of variable and Laplace transformation of the well known semi-infinite integral solutions for the fields[5] yields exact, closed form expressions for the real time-dependent transient fields corresponding to a step current ($I = I_0 u(t)$) excitation of the line source. The y component of the electric field above the half-space ($z \leq 0$) is given by

(5) $$F^U_{yo}(z,t) = \frac{-\mu_0 I}{2\pi}\left[\frac{1}{\sqrt{t^2 - \left(\frac{z+h}{c}\right)^2}}\, u\left[t - \left(\frac{z+h}{c}\right)\right] + \frac{1}{\sqrt{t^2 - \left(\frac{z-h}{c}\right)^2}}\left\{\frac{t - \sqrt{t^2 + \left(\frac{z-h}{c}\right)^2(\varepsilon_{1r} - 1)}}{t + \sqrt{t^2 + \left(\frac{z-h}{c}\right)^2(\varepsilon_{1r} - 1)}}\right\} u\left[t - \left(\frac{z-h}{c}\right)\right]\right].$$

The y component of the electric field within the half-space ($z \geq 0$) is given by

(6) $$F^U_{y1}(z,t) = \frac{-\mu_0 I}{\pi}\,\frac{1}{\sqrt{(t + h/c)^2 - \varepsilon_{1r}(z/c)^2}}\left\{\frac{1}{1 + \sqrt{1 - \left(\frac{z}{c(t+h/c)}\right)^2(\varepsilon_{1r} - 1)}}\right\} u\left[t + \frac{h}{c} - \sqrt{\varepsilon_{1r}}\, z/c\right]$$

For the same excitation and a lossless half-space an exact closed form solution can also be obtained when both the observation point and line source lie on the half-space (z=h=0).

(7) $$F_y^U(x,t) =$$

$$\frac{-\mu_o I}{\frac{\pi x^2}{c}(\varepsilon_{1r}-1)}\left[\sqrt{t^2-(x/c)^2}\,u[t-x/c]-\sqrt{t^2-\varepsilon_{1r}(x/c)^2}\right.$$

$$\left. u[t-\sqrt{\varepsilon_{1r}}\,x/c]\right] .$$

It is suggested that for short times, i.e., times in the vicinity of the waveform origin, these results also hold for a lossy half-space ($\sigma_1 \neq 0$) since setting $\sigma_1=0$ can be interpreted as a high frequency approximation which neglects the conduction currents. Results similar to Eqs. (5) and (6) can also be obtained for the case where the line source lies within the half-space via reciprocity.

If a low frequency or quasi-static approximation where the displacement currents are neglected is made then on the vertical axis (x=0)

(8) $$F_{yo}^U(z,t) = \frac{2\ I\ u(t)}{\pi(h-z)^2\sigma_1} - \frac{2\ I\ e^{\mu_o\sigma_1\frac{(h-z)^2}{4t}}}{\pi^{3/2}\ \sigma_1(h-z)^2}$$

$$\Gamma\left(3/2,\ \frac{\mu_o\sigma_1\ (h-z)^2}{4t}\right)\ u(t),$$

and

(9) $$F_{y1}^U(z,t) =$$

$$\frac{I\ e^{-\mu_o\sigma_1 z^2}}{4\pi\sigma_1 t}\ u(t) + \frac{\mu_o I}{2\pi t}\ e^{-\mu_o\sigma_1 z^2}\ u(t) - \frac{2\ I\ e^{-\mu_o\sigma_1 z^2(1-\frac{1}{4t})}}{\pi^{3/2}\ \sigma_1 z^2}$$

$$\Gamma\left(3/2,\ \frac{\mu_o\sigma_1 z^2}{4t}\right)u(t),$$

where $\Gamma(\nu,x)$ is the incomplete gamma function

$$(10) \qquad \Gamma(3/2,x) = \frac{\sqrt{\pi}}{2} - \sum_{n=0}^{\infty} \frac{(-1)^n \, x^{n+3/2}}{n!\,(n+3/2)} \quad .$$

The results in Eqs. (8) and (9) constitute long time estimates of the transient fields for a step current excitation of the line source.

If the half-space is homogeneous with frequency independent parameters then the response waveforms can at best smoothly decay from the short time estimates in Eqs. (5) and (6) to the long time estimates in Eqs. (8) and (9). This suggests that these results might be combined to yield a simple composite waveform which could then be transformed back to the frequency domain. In our studies of the scattering by objects in free space, such time domain combinations of low and high frequency estimates have been shown to yield surprisingly good approximations in mid-frequency ranges. It is not intended to further pursue this topic during this contract period, but such an approach would appear to merit reasonable consideration in a longer range program.

IV. EXPERIMENTAL STUDIES

Near the beginning of the contract period, preparations for experimental measurements at a remote site (a nearby quarry) which offered hazard-type anomalies were initiated. A pulse generator (H.P. 214A) appropriate for such measurements was ordered. This pulser has a peak pulse amplitude of 50 volts into 50 ohms or 100 volts in 1200 ohms, a 15 ns rise time, pulse widths variable from 45 ns to the μs range and repetition rates from 10 kc to 1000 kc. The major preparations involved replacing a direct interfacing of the antenna system with an instrumentation computer, which had been used on earlier studies, with a recording arrangement such that a non-real time use of the computer was feasible. It should be understood that in an ultimate system the computer functions will be replaced by circuitry. At this stage, however, the computer offers an irreplacable flexibility in processing changes and experimentation. The above mentioned preparations are now nearly completed - certain components have not yet been delivered. The system for remote recording of data resamples the oscilloscope output waveforms at a very low speed with computer control of the sampling point relative to a trigger synched with the scope sweep. As shown in Fig. 13 the trigger and sampling point offset voltage are fed into a phase locked loop. The voltage controlled oscillator (VCO) output drives a one shot which provides the proper pulse shape for triggering the sample and hold amplifier. The offset voltage varies the phase of the VCO output relative to

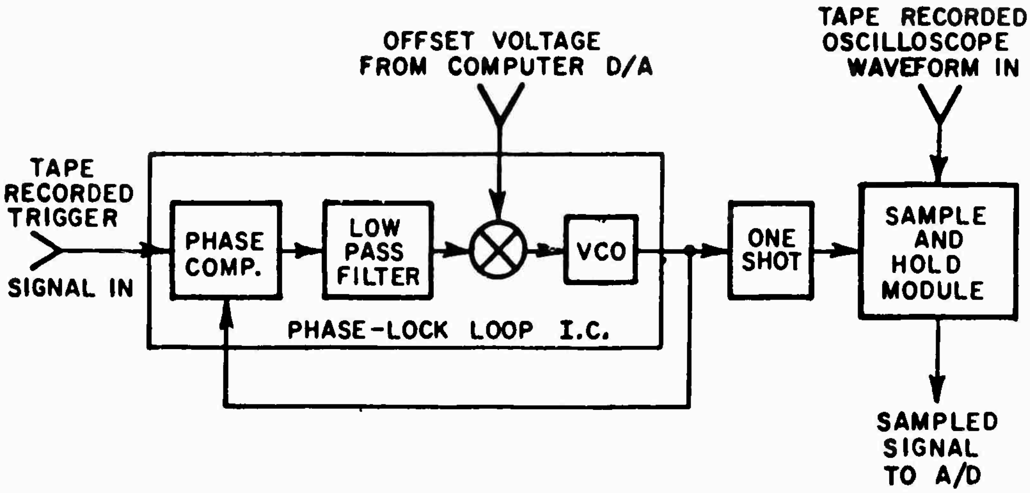


Fig. 13. Data conversion circuit for tape recorded remote site measurements.

the trigger, thus effectively moving the sampling point across the signal waveform. The sampled signal is fed to the computer analog/digital input for conversion to digital form.

A breadboard version of the device is currently being built. A single linear integrated circuit performs the entire function of the phase-locked loop. A miniature hybrid module performs the sample and hold.

The oscilloscope waveforms will be recorded on magnetic tape in the field and the tapes later played back into this device in the laboratory. Since this device does not have to go to the remote site, the breadboard version can be used for actual data conversion as soon as it is operational.

The pulse generator was delivered during the fifth month of the contract; since that date tests of various antenna configurations and preliminary interrogation of certain subsurface targets in the vicinity of the laboratory have been underway using the direct interfacing to the instrumentation computer.

A. <u>First Generation Probe</u>

The basic electromagnetic probe being studied is an insulated, center fed dipole lying on the ground with the ends of the dipole either directly grounded by rods driven into the earth or capacitivly coupled using plates on the ground. The arms of the dipole may be

single wires with ground rods or two wires in a U or V arrangement to two separate ground rods. Alternatively, the dipole arm may be a V-shaped conductor eliminating the need for a ground rod. The system presently envisioned consists of two such dipoles arrayed orthogonally. Two modes of operation are possible; either direct reflection using one or the other of the dipoles as transmitter and receiver or orthogonally using one dipole as a transmitter and the other as a receiver. Both modes are important since the direct mode is sensitive to symmetrical planar stratifications whereas the orthogonal mode is blind to such targets.

A sketch of one version of the probe and a block diagram of the instrumentation is shown in Fig. 14. In Fig. 15, the time domain reflection of one of the dipoles shown in Fig. 14 is shown in the direct reflection mode. The incident pulse for the results shown in Fig. 15 was very long, essentially a step with a 15 ns rise time. Shown in Fig. 15 are the differences when the arms of the dipole are a single wire or two wires in a U or V arrangement. Also shown are the reflected waveforms when the feed cable is terminated in an open circuit, short circuit and a matched load. By adjusting the ground rod depth, the latter portion of the waveform can be reasonably matched to the matched load waveform indicating that at low frequencies at least the antenna is well matched. The effects of tuning by varying the ground rod depths is shown in Fig. 16, these results also indicate that energy is being coupled into the ground.

The waveforms in Figs. 15 and 16 correspond to an incident pulse with approximately a 2 volt peak amplitude. Attempts to operate the probe in either the direct or orthogonal mode using the peak output of the pulse generator revealed that the balun (transformer) used to go from 50 ohms unbalanced to 200 ohms balanced was saturating at a level well below the peak output of the pulser. This is not a basic difficulty since baluns with a higher power handling capability are available and have been ordered. In the interim before their delivery however, the pulser cannot be used at output levels appropriate for interrogation of subsurface targets. Tests did establish however that the probe was insensitive to surface structures (an automobile driven into various quadrants of the probe had no effect for a low level incident pulse) and that a synthetic target in the form of two conducting plates connected electrically could be detected.

The temporary balun difficulty was circumvented by going to essentially a smaller version of the probe (the dipole arms became solid conductors in a V shape) and the use of a different pulse generator. The pulser is not appropriate for deep penetration but can be used to interrogate relatively shallow targets. Using this system, a clay drain tile buried at a depth of 3 feet has been detected. The equipment consisted of an pulse generator, a "four-leaf clover" probe lying on the ground surface, and a computer-controlled sampling oscilloscope. The pulse was approximately

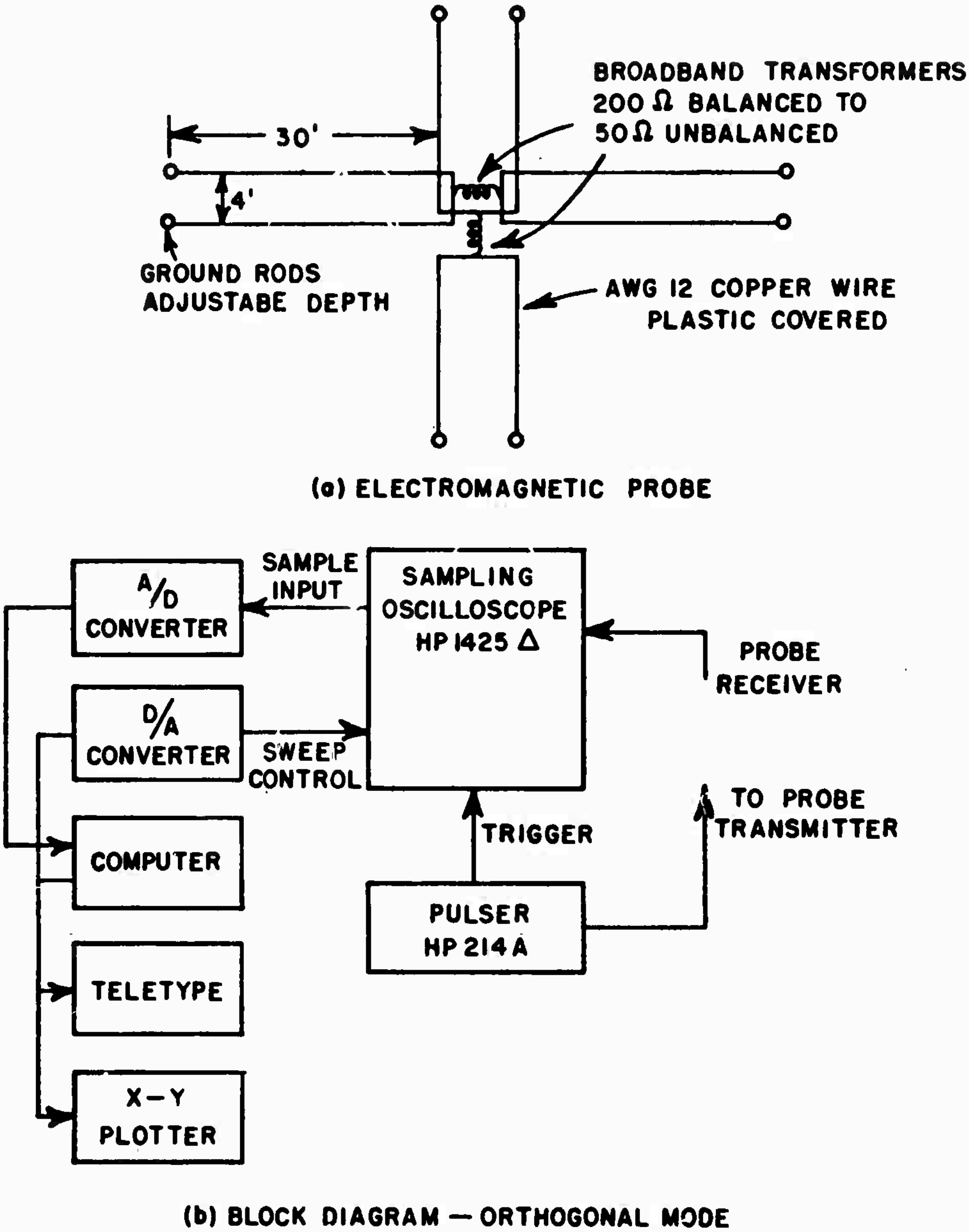


Fig. 14. (a) Electromagnetic probe.
(b) Block diagram of pulse sounding system.

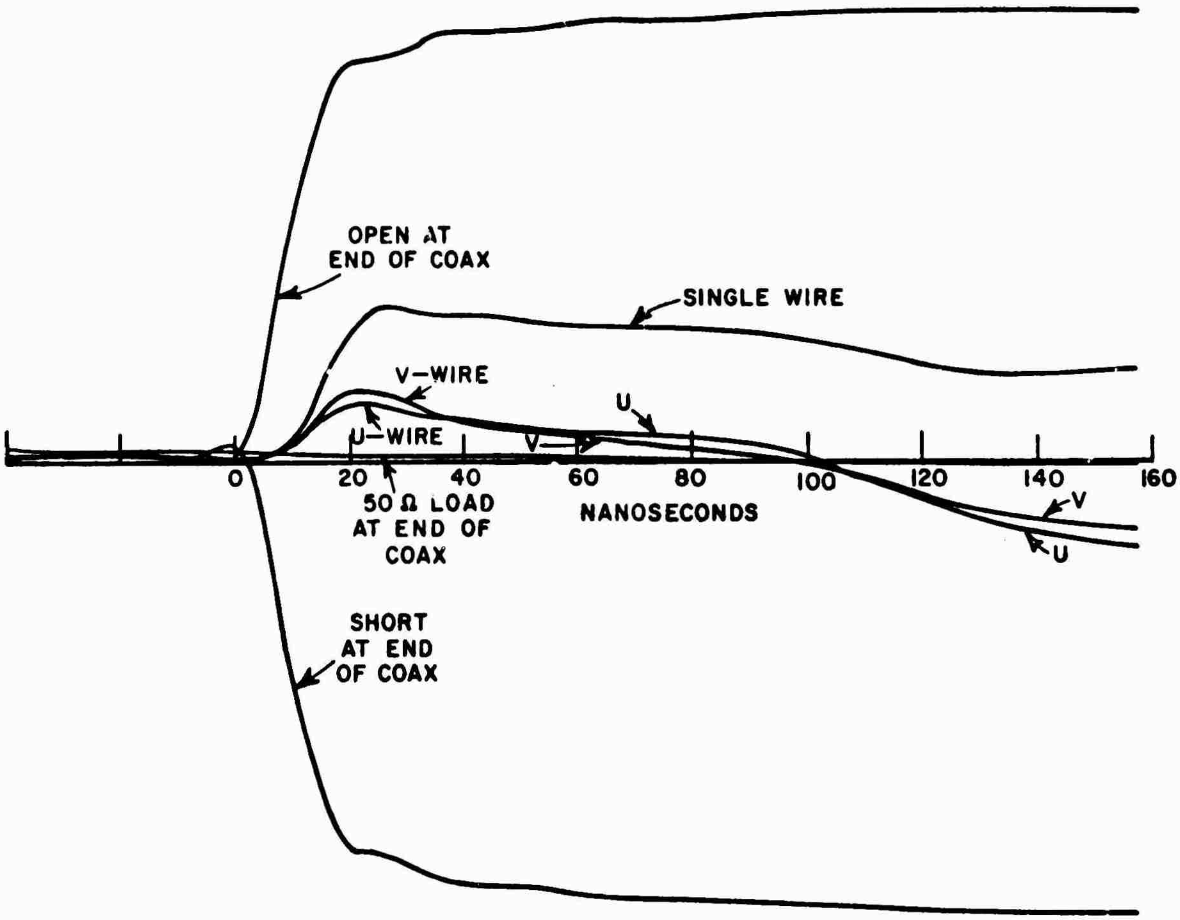


Fig. 15. Direct reflection mode of one probe, various terminations.

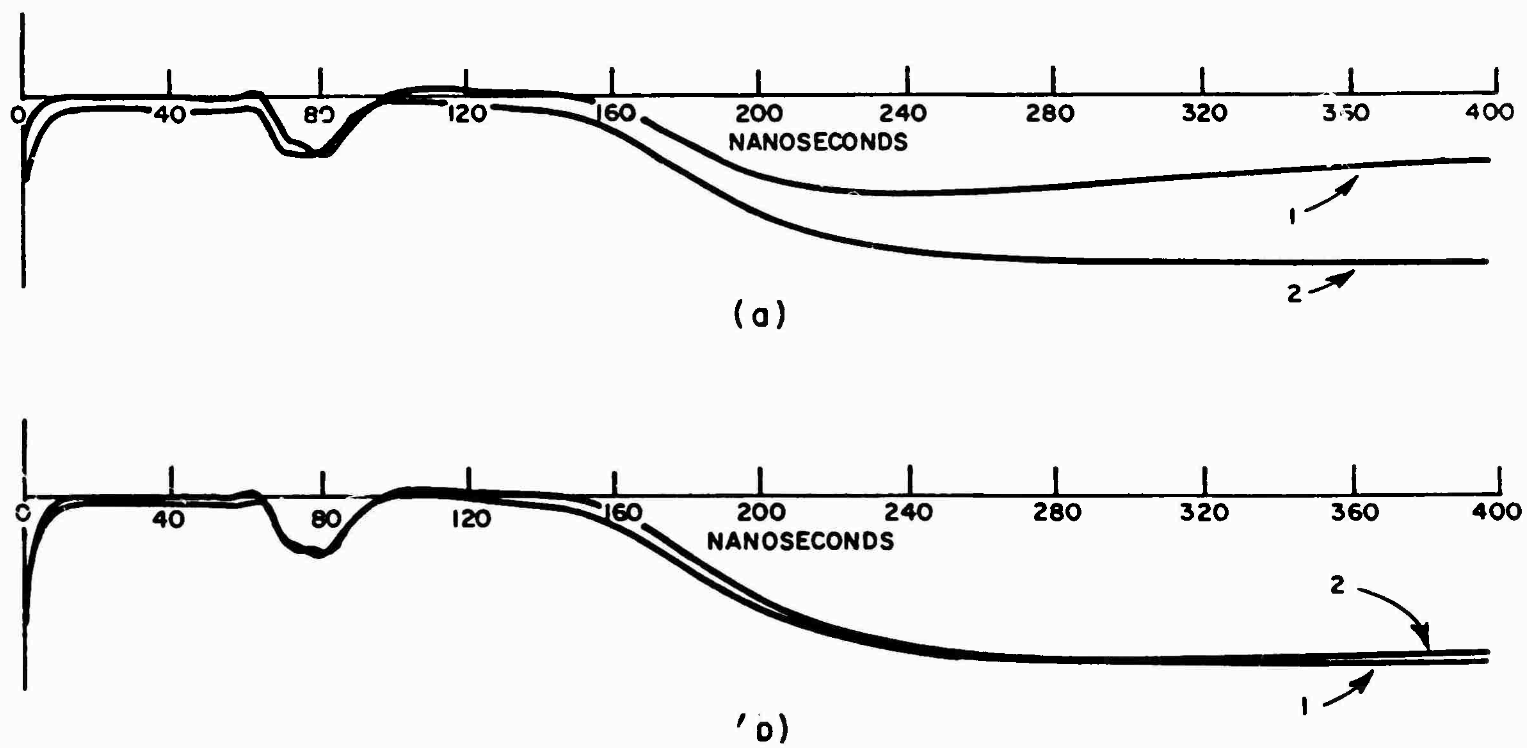


Fig. 16. Direct reflection mode of one probe - effect of ground rod depth.

2 nsec long with a peak amplitude of 10 volts, and a pulse repetition rate of approximately 1 MHz. A sketch of the antenna is shown in Fig. 17.

The antenna was located in several positions in the vicinity of a storm drain-tile line running behind the laboratory building at about a 3 foot depth. Several locations over the drain tile and several locations of assumed "target-free" ground were measured, and the differences between the "target" and "no-target" waveforms were computed and plotted as shown in Fig. 18. Difference curves for target-free ground are shown in Fig. 19. These can be considered to represent the clutter level. These curves demonstrate that the pipe is visible to the system, and that several features of the return waveforms remain constant from one location over the pipe to the next. Based on the variation of these return waveforms it is estimated that the signal-to-clutter ratio of the pipe signature is about 10 dB.

Several measured difference waveforms of the catch basin at the end of the drain tile are shown in Fig. 20. Comparison of these waveforms with those of Fig. 18 indicates that the nature of the return signal is sensitive to the shape of the underground target. Thus, identification of underground object shape from these signature waveforms seems feasible.

B. Propagation Test

While it is not presently possible to use the probe in Fig. 14 with high power because of the balun saturation, the dipoles can be used as receivers. For the transmitter, the balun requirement can be eliminated by going to an unbalanced antenna. To this end a monopole antenna consisting of a 2 foot rod on a circular (1-1/2 foot diameter) ground plane was constructed. In operation, the ground plane rests on the ground with the rod driven into the ground. This antenna can be fed directly by coaxial cable. Results of transmission tests using the monopole as a transmitter and the probe of Fig. 14 as a receiver are shown in Fig. 21. The monopole was near broadside to one dipole and near endfire to the other and located at a distance of 160 feet from the vertex of the probe. The transmitted pulse had a pulse amplitude of 50 volts, a pulse width of 50 nanoseconds, and a repetitive rate of 10 KHz. It was established that the received waveform shown was not the effects of a surface wave by moving a large conducting screen in the vicinity of the monopole without disturbing the received waveform. It is not yet understood why the received waveforms are identical and further measurements are in progress. It has not been established as yet what penetration depths are being achieved; with the monopole as a transmitter it is possible that energy is being confined close to the surface of the ground. Measurements are presently in progress to establish the penetration achieved as well as the attenuation vs frequency for the local ground.

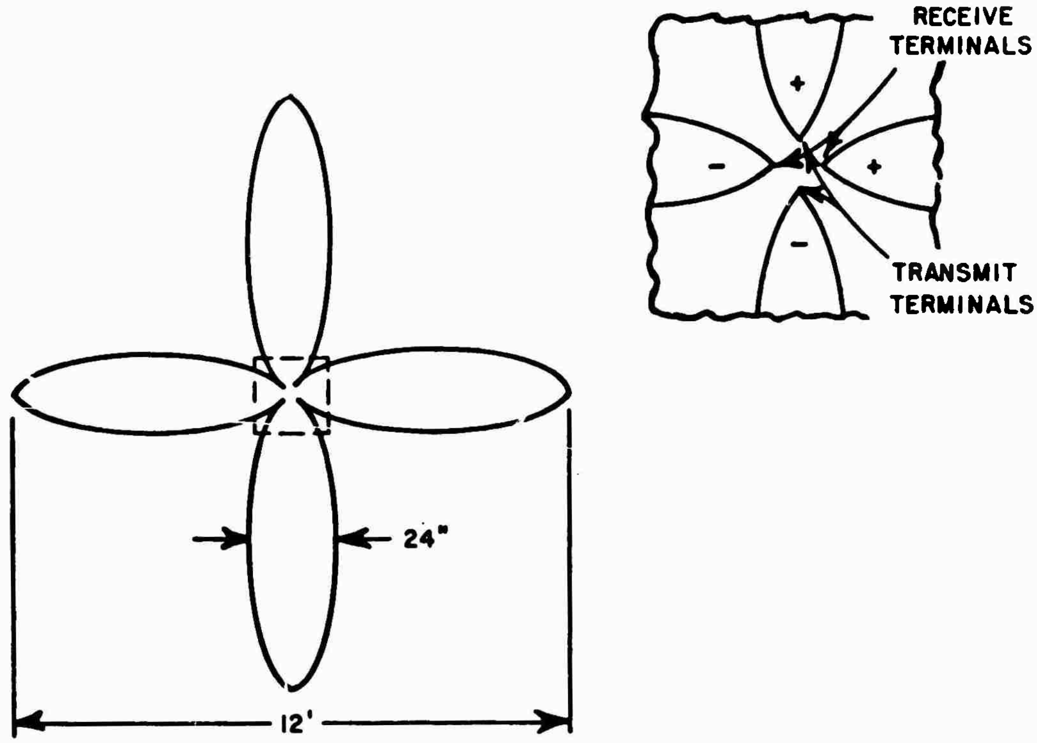


Fig. 17. Sketch of "four-leaf clover" probe.

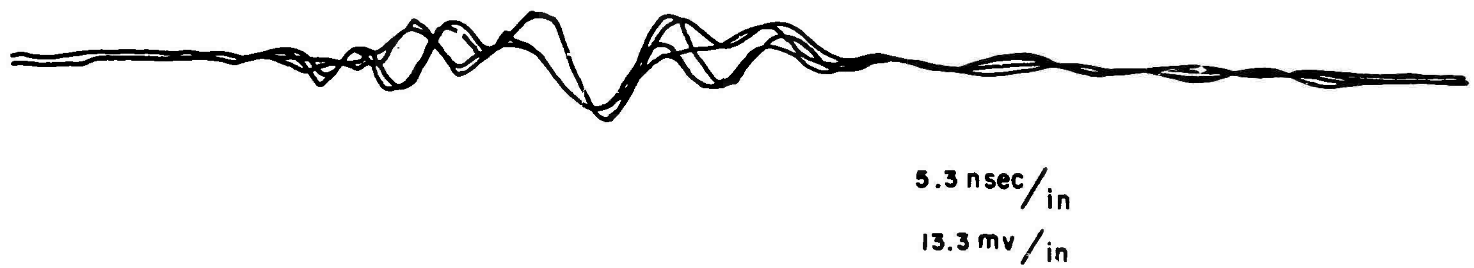


Fig. 18. Drain-tile target difference waveforms.

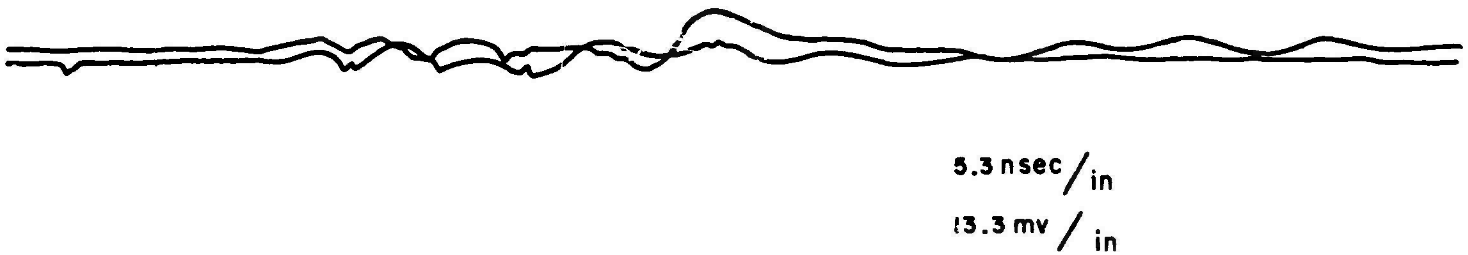


Fig. 19. No-target difference waveforms.

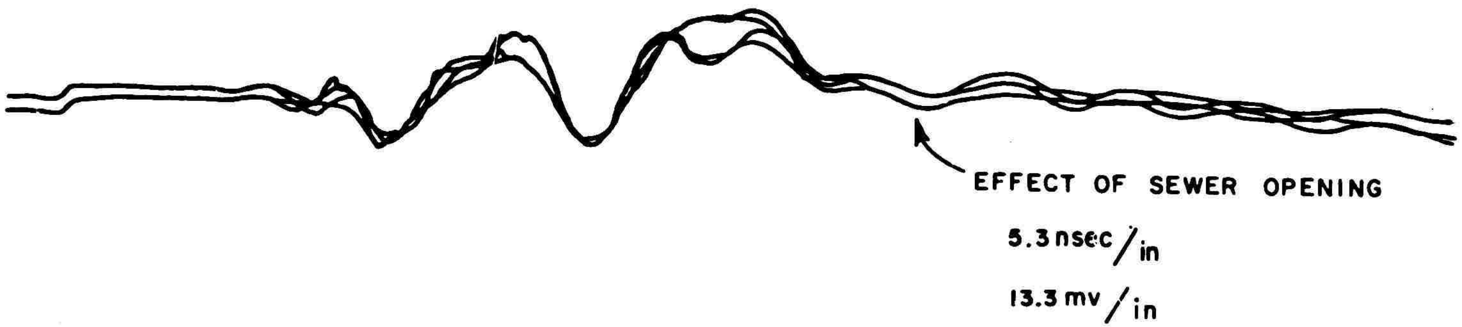


Fig. 20. Catch basin target difference waveforms.

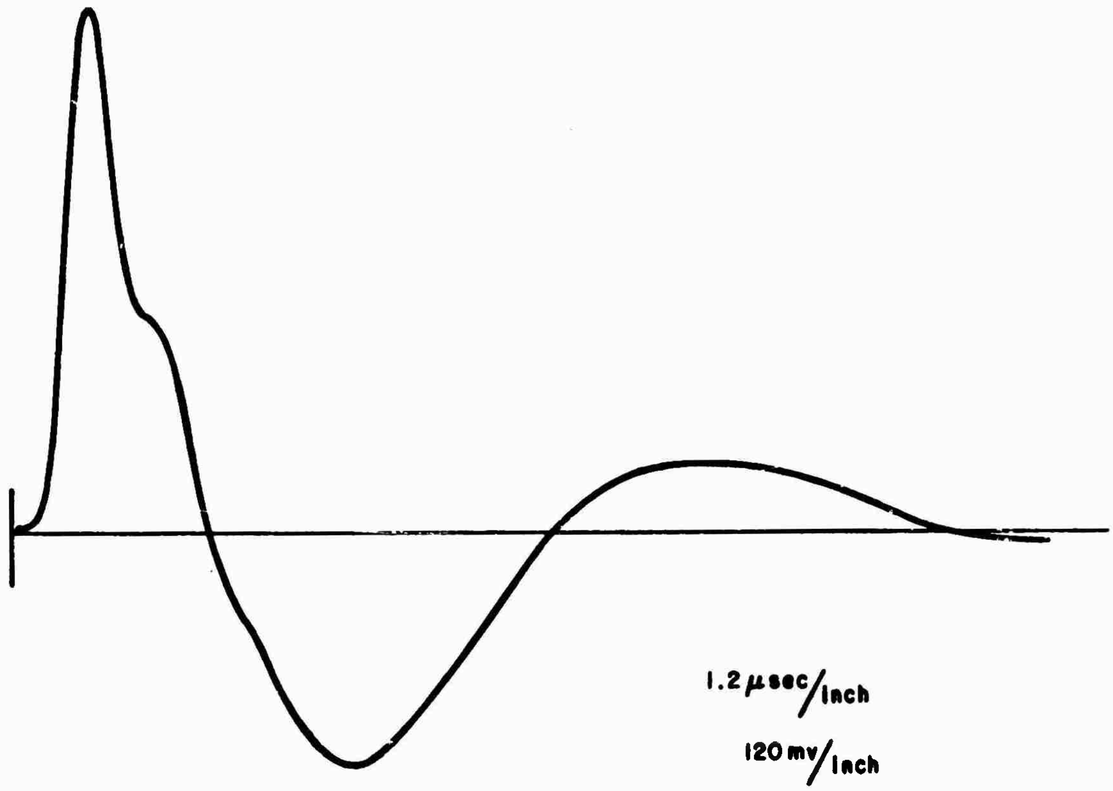


Fig. 21. Received pulse waveform.

VI. CONCLUSIONS

The plane wave scattering by planar conductivity contrasts has been explored via the impulse response waveform for the contrast. A Fourier synthesis technique is utilized to determine the decay rate of the waveform and will be used to explore the effects of frequency-dependent constitutive parameters. The response waveform has a distinctive signature and diagnostic features for both the dielectric constant and conductivity contrasts.

Computer programs for computing the plane wave scattering by arbitrary spherical targets in a dissipative medium have been written and verified, including the case of layered spherical targets. Calculations for realistic spherical-type tunneling hazards and for deducing characteristic response waveforms for such hazards are in progress.

The attenuation and dispersion effects of a lossy overburden have been estimated by assuming plane wave propagation and utilizing the free space scattering characteristics of spherical, cylindrical and disk targets. These results indicate that interface and overburden effects do not preclude unique signatures for the targets.

Exact, closed form expressions for the transient fields of a line source in the presence of a dielectric half-space have been obtained for particular observer locations. Quasi-static estimates of the transient fields for a lossy half-space have also been obtained. From these results, simplified estimates of the fields of a line source in the presence of an arbitrary half-space appear to be feasible.

A comprehensive analysis and computer program for all types of wire probes in a homogeneous dissipative medium have been developed. With these tools, design data for pulse sounding probes to interrogate at various depths are being prepared.

Initial measurements have been made on two versions of the electromagnetic pulse sounding probe. The results indicate that the probe can be well matched, does couple energy into the ground and is insensitive to surface targets. The presence of a clay drain tile at a depth of 3 feet has been detected using a small version of the probe and a pulse generator inappropriate (at least where a lossy overburden exists) for deep penetration. The limited power handling capability of transformers used to match the unbalanced coaxial feed to the balanced probe has temporarily precluded use of the full scale probe with the high power pulse generator. Larger transformers have been ordered and other schemes for eliminating the need for transformers are being studied.

Transmission tests demonstrating that pulsed electromagnetic energy can be propagated through the ground over considerable distances (160 feet) have been made. The energy may be confined to shallow depths, and this possibility is being explored

VII. FUTURE PLANS

It is intended that major emphasis during the remaining contract period will be concentrated on experimental measurements of subsurface targets, first at this laboratory and then at a remote test site where anomalies characteristic of tunneling hazards are available. This is in accordance with the original research plan.

Analytical studies will be primarily devoted to the wire antenna analysis from which realistic dispersion, attenuation and penetration calculations as well as probe design data are possible. The scattering from spherical contrasts will be calculated for hazard-type parameters and response waveforms obtained via Fourier synthesis. Introduction of frequency-dependent constitutive parameters will be made for both the antenna analysis and spherical scatterer program.

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